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Climate of the Past Discussions

An independently dated 2000-yr volcanic record from Law Dome, East Antarctica, including a new perspective on the dating of the c. 1450s eruption of Kuwae, Vanuatu

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Abstract

Volcanic eruptions are an important cause of natural climate variability. In order to improve the accuracy of climate models, precise dating and magnitude of the climatic effects of past volcanism are necessary. Here we present a 2000-yr record of Southern Hemisphere volcanism recorded in ice cores from the high accumulation Law Dome site, East Antarctica. The ice cores were analyzed for a suite of chemistry signals and are independently dated via annual layer counting, with 11 ambiguous years by the end of the record. Independently dated records are important to avoid circular dating where volcanic signatures are assigned a date from some external information rather than using the date it is found in the ice core. Forty-five volcanic events have been identified using the sulfate chemistry of the Law Dome record. Comparisons between Law Dome and NGRIP (Greenland) volcanic records suggest Law Dome is the most accurately dated Antarctic volcanic dataset and allows for the records to be synchronized with NGRIP, leading to an improved global volcanic forcing dataset. Volcanic sulfate deposition estimates are important for modeling the climatic response to eruptions. The largest volcanic sulfate events in our record are dated at 1458 CE (Kuwae, Vanuatu), 1257 and 423 CE (unidentified). Using our record we refine the dating of previously known volcanic events and present evidence for two separate eruptions during the period 1450–1460 CE, potentially causing confusion in the assignment of the Kuwae (Vanuatu) eruption to volcanic signatures during this time interval.

1 Introduction

Understanding natural causes of climate variability is vital to evaluate the relative impacts of human populations, and of all the natural causes, volcanic eruptions and solar variation are the two most important (Gao et al., 2007). Volcanic eruptions are an important part of the global climate system because of their radiative forcing (Zielinski, 2000). Sulfur-rich gaseous emissions from eruptions undergo atmospheric oxidation to form stable aerosol compounds that may remain in the atmosphere for several years, during which time they act to cool Earth's surface by reflection of solar radiation (Rampino and Self, 1984; Robock, 2000). Periods of cooling associated with volcanic eruptions must be adequately accounted for in order to determine natural variation in climate, and interpret anthropogenic influences on the climate system (Robock, 2000). By calculating estimates of the total sulfate deposition to the ice sheet from a volcanic eruption (volcanic flux), we can produce an estimate of the atmospheric loading associated with that event, thus informing us on the climatic impact of the eruption. Volcanic aerosols from major eruptions are transported globally through the stratosphere and are deposited with precipitation all over the world including high latitude polar areas. Ice cores retrieved from these areas offer an archived record that can be analyzed (e.g. measuring the electrical properties or sulfate content of the ice) for the unique signature of volcanic events preserved within them. The development of accurately dated volcanic chronologies, combined with volcanic deposition estimates is key to producing a reliable record of volcanic aerosol loadings.

Producing an accurate volcanic chronology relies upon having a well-dated ice core record. Frequently, however, there are circular arguments whereby volcanic signatures in ice core records are assigned a date based on some external information (e.g. historical documents, tree ring records, and other ice cores) and those assignments are used to date the ice core (e.g. Delmas et al., 1992; Cole-Dai et al., 2000). A number of ice core records, especially those from low accumulation sites where accurate layer counting cannot be performed, use this method. While this method can produce a reasonably accurate timescale for ice cores, it is important to understand the limitations of non-independent dating methods such as this. Incorrect external information will cause errors in the timescale, the assignment of dates does not advance the dating accuracy of the volcanic record – the record will only be as accurate as the record it has been synchronized to, and has the potential to inadvertently reinforce the acceptance of an initially questionable date with little hesitation. Cores dated by non-independent methods remain essential to understanding the spatial distribution patterns of volcanic

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sulfate aerosols, and dating of deep ice where layer counting cannot be reliably performed. Therefore, when using this method, it is important to ensure the most accurate event dates possible are used to minimize errors in the timescale produced. Often it is difficult to obtain reliable stratigraphic time markers beyond recent history, especially in the Southern Hemisphere (SH), as historical documentation of eruptions is poor. Volcanic records obtained from accurately layer counted ice cores, and are independent of previously reported volcanic event dates, are key to producing high-accuracy volcanic chronologies which can improve on the dating of volcanic events recorded in the first millennium CE.

The ice cores used in this study were retrieved from the Dome Summit South (DSS) site, Law Dome (66°46′11″ S, 112°48′25″ E). The DSS site is located on a small coastal ice cap in Eastern Antarctica and is characterized by high annual accumulation (0.70 m yr^{-1} ice equivalent), relatively low mean surface temperatures (−21.8 °C) and wind speeds (8.3 m s^{-1}) (Morgan et al., 1997). Precipitation events at Law Dome occur on average with sufficient frequency to preserve signals at monthly resolution (McMorrow et al., 2001). This allows for high-resolution sampling and this study provides an independently dated, seasonally resolved trace chemistry record spanning the past 2000 yr.

2 Dating and chemical analysis

The Law Dome record was independently dated using annual layer counting of a suite of chemistry species with seasonally defined behaviors. These include oxygen isotopes ($\delta^{18}O$), deuterium (δD), hydrogen peroxide (H_2O_2), non sea-salt sulfate ($nssSO_4^{2-}$) and sea salt species (Cl^-, Na^+ and Mg^{2+}). Additionally, the ratio of SO_4^{2-}/Cl^- was used as a summer marker. Ice core sampling and analysis methods used were described by Palmer et al. (2001) and Roberts et al. (2009). At 23 BCE, annual layer thickness is reduced to 0.25 m yr^{-1} ice equivalent as a result of layer thinning due to ice flow. At this depth, trace ion chemistry was sampled at 2.5 cm resolution, allowing for 8–10 samples

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per year, which is sufficient for annual dating. Analysis of $\delta^{18}O$ was conducted at 1cm resolution. Following the methods of Morgan and van Ommen (1997), the summer maxima in $\delta^{18}O$ were fixed as 1 January of each year horizon. Where $\delta^{18}O$ was unavailable, the δD or $nssSO_4^{2-}$ maximum was used. Dating of the discrete samples was performed using linear interpolation between year depth horizons. Eruption dates previously published for Law Dome (Palmer et al., 2001) older than 1818 CE have been adjusted for a 1-yr dating error due to a damaged section of core. This adjustment was made after synchronizing the chemistry of a new core retrieved from DSS in 2005 to the existing DSS core across the period in question.

Layer counting identified 11 ambiguous years where the seasonality was not clear. Of these 11 yr, 7 yr were not counted where evidence for a year was weak, but could not be conclusively discounted. Four years were counted where multiple lines of evidence supported a year. This error estimation technique allows the date at 23 BCE to be a maximum of 7 yr older or 4 yr younger than dated.

3 Determination of volcanic signals

To identify the signal associated with volcanic eruptions, it was necessary to calculate the non sea-salt sulfate ($nssSO_4^{2-}$) parameter by removing the seawater sulfate component from the total measured sulfate concentration. This is calculated using the following equation:

$$nssSO_4^{2-} = \left[\text{total } SO_4^{2-}\right] - (0.1201 - r) \cdot \left[Na^+\right] \quad (1)$$

where 0.1201 is the ratio of SO_4^{2-} to Na^+ in seawater, and r is a fractionation correction (0.033) to account for sulfate depletion from the formation of frost flowers on sea ice (Rankin, et al., 2000). The $nssSO_4^{2-}$ signal at Law Dome is dominated by strong seasonality associated with the biogenic sulfate cycle. The biogenic sulfate

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seasonality acts as a barrier to accurately resolving the onset and duration of volcanic signals. To reduce the effect of the biogenic signal, we calculated the residual $nssSO_4^{2-}$ ($[nssSO_4^{2-}]_{residual}$). The $nssSO_4^{2-}$ record was down-sampled into 8 samples per year, reflecting the lowest average number of samples per year at 23 BCE. A 31-yr centered moving average (starting in 1995) was computed from the downsampled $nssSO_4^{2-}$ record, and then subtracted from the raw $nssSO_4^{2-}$ record. The 31-yr running mean was used to account for natural variations in background sulfate. Large volcanic events already identified in the record were removed prior to calculation of the residual to avoid incorrectly weighting the ensemble, which would lead to an over-estimation of background sulfate concentrations.

Volcanic signatures were identified by examining the $[nssSO_4^{2-}]_{residual}$ record for departures above background values. Such departures are most evident during winter periods when the biogenic sulfate concentration is relatively low. Additionally, a 6-month duration threshold was set to reduce the chance of mis-identification of any natural variability in the record as volcanic in source. Following the methods of Palmer et al. (2002), eruption signatures were identified by visual study of the $[nssSO_4^{2-}]_{residual}$ record.

Estimates of volcanic sulfate provide information on the climatic effects of volcanic eruptions as the amount of sulfur-rich gas emitted by eruptions can have an effect on global temperatures. The volcanic flux deposition estimates for Law Dome (Table 2) are calculated from the residual $nssSO_4^{2-}$ record according to Eq. (2).

$$f_s = \left[nssSO_4^{2-}\right]_{residual} \cdot \rho \cdot l \cdot 10^{-3}, \ kg^1 \ km^{-2} \quad (2)$$

where $[nssSO_4^{2-}]_{residual}$ is the residual $nssSO_4^{2-}$ in $\mu g\,kg^{-1}$, $\rho = 917\,kg\,m^{-3}$ – the density of ice, and l is the surface equivalent ice length of each sample (in metres) and corrects for the smaller apparent sample depositions due to thinning of the ice with increasing depth. We report total volcanic deposition derived by summing the individual sample depositions to give a total deposition for the duration of the event. Law Dome depositions estimates from this study are different from those discussed for Law Dome

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in Palmer et al. (2002). The differences result from the residual calculation method used and small improvements in Law Dome flow thinning calculations (used in the calculation of *l*) and fractionation corrections (*r* in Eq. 2). Table 2 includes sulphate depositional information from the NGRIP ice core for inter-hemispheric volcanic events. The calculation methods for the NGRIP depositional information this can be found in Appendix A. The inclusion of volcanic sulfate information permits more accurate forcing estimates over longer time series, thus allowing climate models to better simulate the climatic effect of volcanic eruptions.

4 Volcanic eruption dating

Atmospheric transport of volcanic aerosols from eruption site to deposition site results in a time delay of typically 6 months to 1 yr, and is dependent upon eruption location, atmospheric circulation patterns and site precipitation characteristics. Estimates of this time delay are made by comparing the onset of the volcanic signal in a dated ice core record to the eruption date of well-documented eruptions (e.g. Tambora, Krakatau). At Law Dome, the average delay is 1 yr ($1\sigma = 0.58$ yr, $N = 11$). The shortest delay of 0.6 yr was associated with the 1815 CE eruption of Tambora, Indonesia, and the longest delay observed was 2.5 yr for the 1982 CE eruption of El Chichón, Mexico. Palmer et al. (2001) suggested unusual atmospheric patterns associated with the quasi-biennial oscillation could be responsible for this extended delay. 1982–1983 CE corresponds with a strong El Niño-Southern Oscillation event that produced anomalous atmospheric circulation patterns over high southern latitudes (Houseago et al., 1998). Those anomalies could have affected the transport of volcanic aerosols following the El Chichón eruption.

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5 Results and discussion

Signatures of 45 eruptions have been identified from the Law Dome nssSO_4^{2-} record and we have compared our record to other independently, annually dated ice core and tree ring volcanic records (Table 1). A comparison of the dates of globally significant volcanic events between Law Dome and NGRIP (Greenland) and Antarctic cores Dronning Maud Land (DML) (Traufetter et al., 2004) and South Pole (SP04C5) (Ferris et al., 2011) is shown in Fig. 2. Figure 2 illustrates the number of years of difference between the dates of events observed in Law Dome and the three other ice cores. Volcanic events identified in each record were matched based on their eruption signature characteristics (e.g. signature shape, magnitude). Comparisons with NGRIP show good agreement, averaging a 1 year difference, with a maximum of 3.3 yr difference between volcanic deposition dates over the past 1800 yr. The NGRIP data is on the GICC05 timescale (Vinther et al., 2006) and was used by Gao et al. (2008) in 1-yr resolution as part of their global volcanic forcing reconstruction. Here the NGRIP SO_4^{2-} data are used in full resolution (see Appendix A). The agreement between Law Dome and DML for the period 2000–1000 CE is good, with the exception being the 1450s eruption that is attributed to Kuwae (discussed below). The two records do not agree as closely from 1000–172 CE, with the DML record drifting slowly to be 22 yr younger than Law Dome at the 164 CE (Law Dome) event. Comparisons of the Law Dome and South Pole records show the South Pole record to be more variable, drifting 10 yr older than Law Dome, before coming back into agreement for the 531 CE event, and drifting to become 17 yr older than Law Dome by the 164 CE event. The accumulation rate of DML (0.073 m yr^{-1} ice equivalent; Schwander, 2003) and SP045C (0.075 m yr^{-1} ice equivalent; Ferris et al., 2011) is considerably lower than the 0.19 m yr^{-1} ice equivalent of NGRIP (Vinther et al., 2006) and 0.70 m yr^{-1} ice equivalent of Law Dome (Morgan et al., 1997). The relatively low accumulation rates at the DML and SP045C sites may increase the chances of a seasonal cycle being absent or ambiguous in nature, thus contributing to the larger error estimates for these cores relative to Law Dome and

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NGRIP, and may be responsible for the gradual drift in dates relative to Law Dome and NGRIP.

The link between anomalous tree ring width and frost damaged rings has been established in numerous studies (e.g. LaMarche and Hirschboek, 1984; Scuderi, 1990). We have compared the volcanic signals in tree rings from the Northern Hemisphere (NH) bristlecone pine record of Salzer and Hughes (2007) to our Law Dome volcanic record (Table 1). There is agreement on a number of large, globally significant volcanic events. Only eruptions capable of affecting climate in both hemispheres will be identifiable in both records. A notable exception is the 1815 CE eruption of Tambora, Indonesia, which is not detected in their bristlecone pine record. The authors note however there was a reduction in tree ring growth following the 1815 CE eruption of Tambora, but it was not in the lowest 5 % of the record, which was their detection threshold. No frost damaged ring is reported either, however, it is important to note that not all frost damaged rings are the result of volcanic eruptions, and not all eruptions result in frost damaged rings at a given location (LaMarche and Hirschboek, 1984). Other tree ring records (e.g. LaMarche and Hirschboek, 1984; Briffa et al., 1998) have identified the signal of the major 1815 CE eruption of Tambora.

Based on total deposition, the largest volcanic events observed in our record are the 1458 CE (Kuwae?), 1257 CE, 422 CE (Unidentified) and 1815 CE (Tambora) events. The 1458 CE and 1257 CE eruptions appear similar in size when comparing event depositions, approximately 1.8 times greater than Tambora. The 422 CE event is larger than Tambora, however, the signature associated with this event appears bimodal in nature, and may be a result of two separate eruptions in close temporal proximity. The record has a period of minimal volcanic activity between 900–679 CE. Other records from low accumulation Antarctic sites do see volcanic events during this period (e.g. Ferris et al., 2011) suggesting dilution effects of the higher accumulation at Law Dome make smaller or less sulfate rich eruptions comparatively difficult to see. The attribution of eruption sources to sulfate spikes in the 700-yr period 1995–1300 CE was discussed in detail by Palmer et al. (2001). We have not attributed a source to any

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other volcanic signatures in this record apart from the 229 CE event. Although the start date of this event is not clearly identifiable due to a gap in the sulfate record between 229–230 CE, there is an increase in $[nssSO_4^{2-}]_{residual}$ values between 230–31 CE. We suggest this event may be the major Holocene eruption of Taupo, New Zealand, on the evidence presented in this study, and dendrochonological work by Hogg et al. (2011) placing the date of this eruption at 232 CE ±5 yr.

The accuracy of the Law Dome dating allows us to refine the presently accepted dates of volcanic eruptions. This refinement improves existing reconstructions of global volcanic forcing. The Law Dome eruption signature at 566 CE is in agreement with the NH date for the volcanic index of Gao et al. (2008). We do not observe any eruption in the Law Dome record that is in agreement with the SH date of 578 CE, although we note that it is in agreement with DML. Larsen et al. (2008) suggested that the sequence of volcanic signals detected in the DML ice core at 542, 578 and 685 CE corresponds to the sequence of volcanic signals detected in Greenland ice cores at 533, 567 and 675 CE. The Law Dome record essentially confirms this interpretation, as the accurate dating places the sequence at late 530, 566 and 676 CE closely matching the Greenland GICC05 dates. The South Pole (SP04C5) ice core (Ferris et al., 2011) has an event dated 560 CE with an error of approximately 2 %, which also places it within agreement of the NH dating for this eruption, and it is likely the same event in all four ice cores. The distinct volcanic horizon dated late 530 CE at Law Dome is in close agreement with the 533 CE NGRIP date for this event. There is also a volcanic event dated 531 CE in the SP04C5 ice core. By confirming the Larsen et al. (2008) interpretation that these three events were global, the forcing associated with these events changes by a substantial amount.

6 Dating of the major 1450s CE eruption

The largest sulfate spike observed in our 2000-yr record is an eruption with a deposition date commencing in mid 1458 CE, and a total deposition of 108.57 kg H_2SO_4 km^{-2},

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over 2.6 yr. Numerous ice core and tree ring chronologies have recorded a signature of a large volcanic eruption dated in the 1450s (e.g. Langway, 1995; Delmas et al., 1992; Cole-Dai et al., 1997; Clausen et al., 1997; Briffa et al., 1998; Salzer and Hughes, 2007; Ferris et al., 2011). The eruption has been linked to the Kuwae caldera, Vanuatu. Because this event is one of the largest in the last two millennia, it is important to constrain the timing of the event so that the effect on the climate is correctly represented in global climate models.

Despite the magnitude of this event, the dating remains uncertain. Gao et al. (2006) attempted to constrain the dating by synchronizing multiple ice core and tree ring records, and examining historical documents, concluding that Kuwae was a single-phase eruption event, and likely erupted in either 1452 or 1453 CE. Our layer-counted dating places this large event at 1458 ± 1 yr, and when considering the uncertainties with dating errors, the longest transport delay with precedent (2.5 yr), the earliest eruption date based on this work is 1455 CE. Comparisons of Law Dome and other layer-counted SH records; DML, Siple Station (Cole-Dai et al., 1997) and SP04C5 (Ferris et al., 2011) yields deposition dates for the large sulfate peak of 1453 ± 5 CE in DML, 1454 ± 3 CE at Siple Station and 1453 ± 7 CE in SP04C5. This allows for a maximum date range of 1448–1458, 1451–1457 and 1446–1460 CE respectively. The higher accumulation rate and larger suite of measured ions available at Law Dome in comparison to the other SH records allows for better constrained error, giving a deposition date range of between 1457 and 1459 CE. By comparing errors in the records, the common time period for this eruption deposition is between 1457 and 1459 CE, with the eruption taking place in 1456 CE. No event is observed at Law Dome during 1453 CE, however there is a small gap in trace chemistry during this period.

Though the eruption signature assigned to Kuwae appears as a single large event in available Antarctic records, the picture is more complicated in NH ice cores, with several records showing a peak in the mid and late 1450s CE (Gao et al., 2006). Sulfate data from the independently layer-counted Greenland NGRIP ice core reveals two clear eruptions, at 1453 and 1458 CE (Fig. 3). The Crête (Greenland) ice core (an

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independently dated, annual layer counted record) displays a similar timing and signature (see Gao et al., 2006, Fig. 3). The layer counted DYE-3 (Greenland) record shows only one volcanic event during this period, dated at 1457 CE (Clausen et al., 1997). GISP2 (Greenland) was sampled at a bi-annual resolution and has one volcanic signature also, dated 1459 CE (Zielinksi, 1995).

Unusual weather and atmospheric events during 1453 CE has been attributed to Kuwae (Pang, 1993), however such circumstantial evidence is not conclusive of an eruption location. LaMarche and Hirschboek (1984) identified a frost ring in 1453 CE in records of bristlecone pines from the western USA. Salzer and Hughes (2007) reported frost damaged tree rings in bristlecone pines in 1453 and 1455 CE, frost damaged rings in 1457–1458 CE and ring width minima through the period of 1459–1462 CE. They proposed the 1453 CE tree ring signature is representative of Kuwae, while the later frost damage and width minima signals are related to Pelée (Martinique). Briffa et al. (1998) assigned the date of Kuwae to 1453 CE, coinciding with a large decrease in tree ring density. Bigler et al. (2002) raised the possibility that the sulfate peak present in their B20 ice core (Greenland) may be the result of more than one eruption, Kuwae and Anianchak, Alaska. Briffa et al. (1998) also notes Anianchak as a possible source of volcanic aerosols in the 1450s CE that may have contributed to the cooling and decrease in tree ring density reported.

Considering the evidence, we propose that there were two volcanic eruptions during 1450–1460 CE. A number of NH records clearly demonstrate two signals, while the SH ice cores show only one. This implies either that one of the eruptions had a greater impact on NH climate, or that the SH cores were not in localities sensitive to this eruption source. The 1458 CE event at Law Dome is in close agreement (±2 yr) with the late 1450s eruption signature identified in several independently dated, layer counted NH ice core chronologies and is within the error bounds of the SH records. This suggests the larger, more globally significant eruption is the later, 1458 CE event. Historical evidence and tree ring records suggest that an eruption occurred in the early 1450s, and NGRIP ice core data supports this finding. The size and location (17° S) of

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the Kuwae caldera (Monzier et al., 1994) and sulfur-rich characteristics of the eruption (Witter and Self, 2007) suggests that the larger of the two eruptions (1458 CE) is that of Kuwae. Furthermore the lack of a SH signature of the 1453 CE event, makes it an unlikely candidate for the Kuwae eruption. However, geological evidence for a large mid 15th century eruption of the Kuwae caldera (Nemeth et al., 2007) suggests the eruption at this time was either smaller than first thought, or subaqueous in nature, thus limiting its effect on climate forcing. Until a direct link (e.g. tephra) between the large sulfate spike in ice cores and a volcanic centre is found, it is difficult to safely attribute a source to the 1458 CE event, and as such we urge caution in assigning Kuwae to any eruption signature during the 1450s CE.

7 Conclusions

Using the independently dated, annually resolved ice core record from Law Dome, we have accurately dated 45 volcanic eruption events over the past 2000 yr. A comparison of volcanic horizon dates from our Law Dome record with other independently dated records demonstrates good agreement; particularly with the well dated NGRIP record, where the age difference between major global volcanic horizons is ±3 yr. Our investigation has found evidence for two separate eruptions between 1450 and 1460 CE. This study places the largest eruption during this period at 1458 CE, which is in agreement with multiple Greenland records. A second eruption signature is observed in NGRIP at 1453 CE, in agreement with NH tree ring records and historical evidence. The improved dating of volcanic events in the first millennium for the SH allows current volcanic forcing datasets to be updated and extended. By demonstrating there are two separate volcanic events in the 1450s CE, the volcanic forcing impact changes, and models can be updated to reflect this. Further, our study has confirmed that three 6–7th century eruptions recorded in the Southern Hemisphere can be synchronized to Greenland records, thus increasing their global significance and estimated climate impact, which is important information for reconstructions of past global climate. This study also highlights

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the issue of circularity in dating of volcanic records, and the limitations that places on attempts to improve dating accuracy of volcanic records, particularly prior to historical documentation.

Appendix A

The NGRIP SO_4^{2-} data set is based on measurements performed on two NGRIP ice cores. Data covering 1973–1999 CE stems from the NGRIP 2000 S6 shallow core, while the 186-1973 CE interval derives from the NGRIP 1 1996 main core. The entire data set was measured in 5cm resolution, corresponding to an average time resolution of 4 samples per year in the deepest (oldest) ice and 10 samples per year in the uppermost (youngest) sections of the NGRIP ice.

The measurement data were converted into SO_4^{2-} deposition using Eq. (2) without the sea salt correction. Detection of volcanic signals in the NGRIP 5cm resolution SO_4^{2-} deposition data set was carried out using the methodology outlined in Traufetter et al. (2004). In this approach running medians (RM_i) and median absolute deviations (MAD_i) of a moving window of n data are calculated. Peaks were then found when deposition exceeded the running threshold value:

$$y_r = RM_i + k \cdot MAD_i. \quad (A1)$$

The parameters $k = 5$ and $n = 100$ were determined empirically. Furthermore peak width was defined as the number of samples surrounding a detected sample, all exceedeing a running threshold calculated with $k = 0.5$.

The total volcanic deposition for each event was then calculated as the sum of the deposition stemming from each 5 cm sample forming a given peak, subtracting the background SO_4^{2-} deposition (the background being calculated as the running mean of the SO_4^{2-} deposition data were no volcanic signals were detected, again with $n = 100$

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as the window length). Peak deposition uncertainties were finally calculated from the standard deviation of the background SO_4^{2-} deposition.

The NGRIP sulfate data is available from www.icecores.dk.

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Table 1. Comparisons of the Law Dome volcanic record event dates with other independently dated records.

Volcanic event	Law Dome ice date	NGRIP[1]	DML[2]	NH tree ring signature[4]	South pole[3]
Pinatubo/Cerro Hudson	1991.7	1992	1992	–	1991
El Chichón	1984.5	–	1982	–	–
Agung	1964.1	–	1964	*1965*	1963
Tarawera	1887.5	–	1886	–	–
Krakatau	1884.5	1884	1884	*1884*	1887
Cosiguina	1836.7	1835	1835	1836	1836
Galunggang	1823.4	–	–	–	–
Tambora	1815.8	1816	1816	–	1815
Unidentified	1809.7	1809	1809	*1809*	1808
Unidentified	1695.3 ± 1	1694	1695	–	1687
Gamkonora	1674.3 ± 1	–	1676	1675	1668
Parker	1641.8 ± 1	1641	1640	1641	1634
Huaynaputina	1600.7 ± 1	1601	1601	*1601*, 1602	1600
Ruiz	1596.7 ± 1	–	1596	*1596*	1594
Raung	1595.5 ± 1	–	–	–	–
Kelut	1587.3 ± 1	1586	–	–	–
Billy Mitchell	1583.6 ± 1	1584	–	–	–
Kuwae?	1458.5 ± 1	1458	–	*1457*, 1458–1462	–
Kuwae?	–	1453	1453	*1453*	1453
Unidentified	1344.0 ± 1	1344	1343	1342	1334
Unidentified	1275.6 ± 1	1276	1276	*1275*, *1277*	1274
Unidentified	1268.4 ± 1	–	1268	–	1269
Unidentified	1257.4 ± 1	1259	1256	1257	1260
Unidentified	1229.2 ± 1	1230	1227	1230	1235
Unidentified	1170.7 ± 1	1168	1168	*1171*	1176
Unidentified	1014.6 ± 1	–	–	*1015*	–
Unidentified	956.8 ± 1	–	961	*959*	
Unidentified	924.5 ± 1	–	–	–	–
Unidentified	900.5 ± 1	897 or 901	–	900–903	908
Unidentified	679.2 −4/+1	–	–	*681*	–
Unidentified	676.5 −4/+1	675	685	674	662
Unidentified	566.3 −5/+1	567	578	569	560
Unidentified	530.9 −5/+1	533	542	*532*	531
Unidentified	449.7 −6/+2	–		451	446
Unidentified	422.7 −6/+2	425	441	*421*	411
Unidentified	343.7 −6/+2	–	–	344	–
Unidentified	295.4 −7/+3	297	315	–	288
Unidentified	258.7 −7/+3	258	–	–	–
Taupo?	∼229 −7/+3	230	249	*230*	217
Unidentified	198.4 −7/+3	–	–	–	181
Unknown	163.8 −7/+3		186	–	
Unknown	136.4 −7/+3			137	
Unknown	117.5 −7/+4			*119*	
Unknown	52.5 −7/+4			–	
Unknown	−2.5 −7/+4			–	

All dates CE. [1] See Appendix A for dating methods; [2] Traufetter et al. (2004); [3] Ferris et al. (2011); [4] Salzer and Hughes (2007), tree ring growth minima (plain text) and and frost damaged rings (italics). A – indicates the volcanic is not observed in that record, no mark indicates the record does not cover this period. Unknown events are those not previously reported; unidentified are those previously recorded, but the eruption source is not known.

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Table 2. Volcanic sulphate deposition at Law Dome. For events identified as inter-hemispheric, NGRIP depositional data is provided also.

	Law Dome			NGRIP		
Event	Start date	End date	Deposition ($kg\,H_2SO_4\,km^{-2}$)	Start date	End date	Deposition ($kg\,SO_4\,km^{-2}$)
Pinatubo/Cerro Hudson	1991.7	1993.9	19.50 ± 0.8	1992.1	1992.4	5.5 ± 1.9
El Chichón	1984.5	1984.8	<5.0	–	–	–
Agung	1964.1	1965.2	10.27 ± 0.5	–	–	–
Tarawera	1887.5	1888.2	7.93 ± 0.5	–	–	–
Krakatau	1884.5	1885.9	17.19 ± 0.7	1883.5	1886.2	15.4 ± 2.7
Cosiguina	1836.7	1837.8	8.90 ± 0.5	1835.3	1838.4	33.4 ± 2.1
Galunggung	1823.4	1823.9	6.27 ± 0.9	–	–	–
Tambora	1815.8	1819.3	58.36 ± 1.5	1816.1	1817.9	40.3 ± 1.8
Unidentified	1809.7	1811.1	25.16 ± 1.3	1809.3	1811.8	38.6 ± 2.2
Unidentified	1695.3	1697.2	28.81 ± 1.3	1694.1	1698.0	37.2 ± 2.1
Gamkonora	1674.3	1676.0	15.03 ± 0.5	–	–	–
Parker	1641.8	1643.3	21.76 ± 0.8	1640.9	1643.6	41.6 ± 3.0
Huaynaputina	1600.7	*	*	1601.1	1603.7	48.0 ± 2.4
Ruiz	1596.7	1598.4	20.75 ± 1.6	–	–	–
Raung	1595.5	1596.1	<5.0	–	–	–
Kelut	1587.3	1588.3	8.05 ± 0.7	1586.0	1586.6	5.4 ± 1.1
Billy Mitchell	1583.6	1584.1	<5.0	1583.5	1583.7	2.8 ± 0.7
Kuwae?	1458.5	1461.1	108.57 ± 4.0	1459.2	1461.4	41.4 ± 1.8
Kuwae?	–	–	–	1453.2	1455.2	27.99 ± 1.8
Unidentified	1344.0	1346.2	25.06 ± 1.0	1344.9	1347.7	33.3 ± 2.4
Unidentified	1275.6	1278.0	56.68 ± 1.4	1277.3	1278.5	8.6 ± 1.4
Unidentified	1268.4	1269.4	32.97 ± 2.6	–	–	–
Unidentified	1257.4	1259.2	103.27 ± 4.3	1258.1	1261.8	98.6 ± 2.2
Unidentified	1229.2	1231.1	27.42 ± 1.0	1229.5	1232.7	61.3 ± 3.0
Unidentified	1170.7	1171.9	14.80 ± 0.5	1167.4	1170.4	36.5 ± 1.8
Unidentified	1014.6	1015.9	11.25 ± 0.9	–	–	–
Unidentified	956.8	958.0	15.81 ± 1.1	–	–	–
Unidentified	924.5	925.4	12.08 ± 0.8	–	–	–
Unidentified	900.5	901.1	15.51 ± 0.9	–	–	–
Unidentified	679.2	681.1	19.76 ± 0.9	–	–	–
Unidentified	676.5	677.7	30.47 ± 2.0	674.2	676.7	31.1 ± 2.5
Unidentified	566.3	567.7	25.73 ± 1.5	566.9	569.4	42.9 ± 2.5
Unidentified	530.9	533.2	37.74 ± 1.9	532.1	536.5	56.2 ± 3.7
Unidentified	449.7	452.3	28.45 ± 1.7	–	–	–
Unidentified	422.7	427.0	64.43** ± 1.6	425.1	426.9	17.5 ± 1.5
Unidentified	343.7	345.2	16.40 ± 1.3	–	–	–
Unidentified	295.4	297.0	28.15 ± 1.6	297.1	297.7	8.9 ± 1.3
Unidentified	258.7	260.0	17.47 ± 1.6	258.1	262.1	55.4 ± 2.9
Taupo?	~229	232.3	*	230.1	231.6	10.8 ± 2.0
Unidentified	198.4	200.0	17.49 ± 0.7	–	–	–
Unidentified	163.8	164.9	30.52 ± 2.5			
Unknown	136.4	137.0	13.43 ± 1.4			
Unknown	117.5	120.5	5.52 ± 0.8			
Unknown	52.5	54.1	14.73 ± 0.6			
Unknown	−2.5	1.3	19.92 ± 1.5			

All dates CE. * Eruption signature incomplete. ** Possibly two close eruptions. A – indicates the volcanic event is not observed in that record. The NGRIP record does extend beyond 186 CE. Unknown events are those not previously reported; unidentified are those previously recorded, but the eruption source is not known.

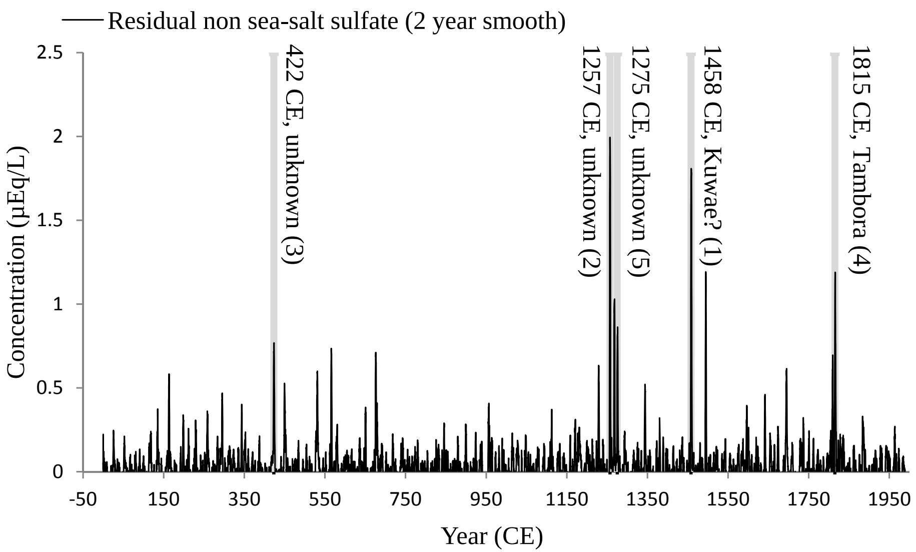

Fig. 1. The Law Dome residual non sea-salt sulfate record. The peaks shaded in grey represent the five largest volcanic depositional events, with the number in brackets signifying event size rank in the Law Dome record. A 2-yr smooth was used for illustrative purposes.

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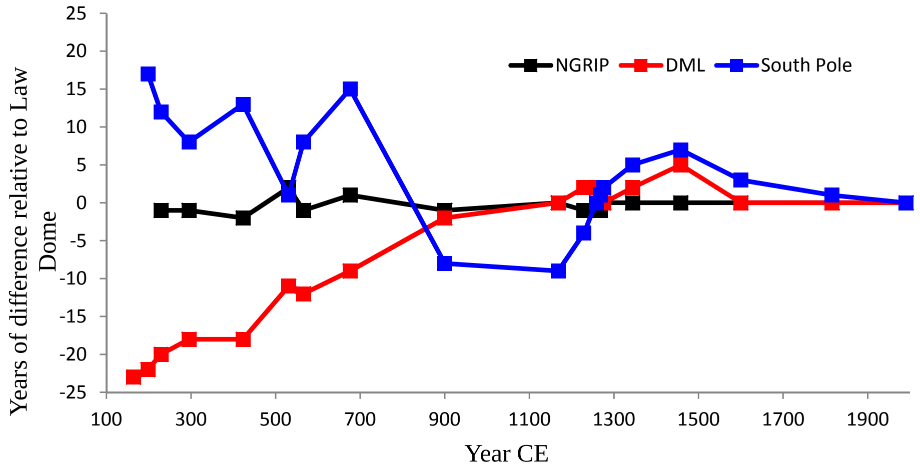

Fig. 2. Comparison of Law Dome to other ice core volcanic records. This figure illustrates the number of years of difference between the dating of volcanic events common to the NGRIP, DML and South Pole (SP045C) ice cores relative to Law Dome. Volcanic event dates have been matched on eruption signature. DML and South Pole cores are from relatively low accumulation sites (0.073 and 0.075 m/ice equivalent per year respectively), which may be a factor in the variability and drifting of those timescales relative to Law Dome (0.70 m/ice equivalent per year). NGRIP at (0.19 m/ice equivalent per year) still agrees well with Law Dome.

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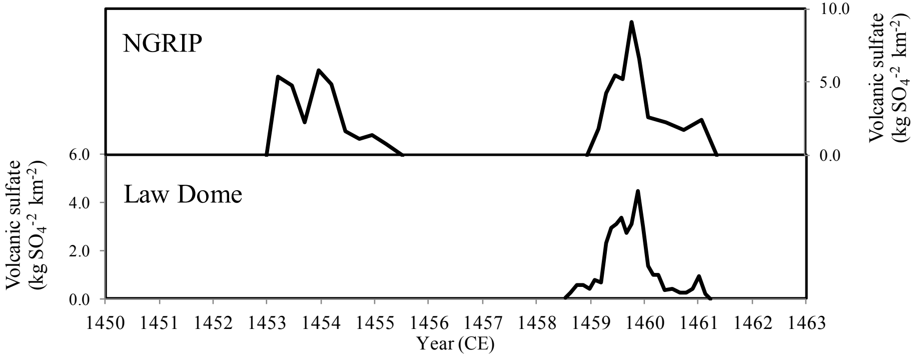

Fig. 3. The Law Dome and NGRIP volcanic sulfate records between 1450–1460. The two distinct volcanic peaks in NGRIP are dated 1453 and 1458 CE, the single clear peak in Law Dome is dated 1458 CE. The two NGRIP peaks are evidence of two separate volcanic eruptions during the 1450s CE.