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Variability of sulfate signal in ice-core records based on five replicate cores

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Abstract

Current volcanic reconstructions based on ice core analysis have significantly improved over the last decades. Relying on limited and disparate sulfate profiles at first, they have progressively incorporated multi cores analysis with high temporal resolution from different parts of the Polar Regions. Regional patterns of volcanic deposition flux are now based on composite records, built from several cores taken at both poles. However, it is worth mentioning that most of the time only a single record at a given site is used for such reconstructions. This implicitly assumes that transport and regional meteorological patterns are the only source of the dispersion of the volcanic-products. In the present work, we evaluate the local scale variability of a sulfate profile in a low accumulation site (Dome C, Antarctica), in order to assess the representativeness of one core for such reconstruction. We evaluate the depth variability, statistical occurrence, and sulfate flux deposition variability of volcanic eruptions detected on 5 ice cores, drilled 1 m away from each other. Local scale variability, essentially attributed to snow drift and surface roughness at Dome C, can lead to a non-exhaustive record of volcanic events when a single core is used as the site reference with a bulk probability of 30 % of missing volcanic events and 60 % uncertainty on the volcanic flux estimation. Averaging multiple records almost erases the probability of missing volcanic events and can reduce by half the uncertainty pertaining to the deposition flux.

1 Introduction

When a large and powerful volcanic eruption occurs, the energy of the blast is sufficient to inject megatons of material directly into the upper atmosphere (Robock, 2000). While ashes and pyroclastic materials fall rapidly on the ground by gravity, gases remain for longer. Among them, SO_2 is of a particular interest due to its conversion to tiny sulfuric acid aerosols, which can potentially impact the radiative budget of the atmosphere (Rampino and Self, 1982; Timmreck, 2012). In the troposphere where turbulence, clouds formation, rain and downward transports are efficient processes to clean the atmosphere, the volcanic sulfuric acid layers rarely survive more than a few weeks and thus have a limited action on the Earth's climate. The story is different when the volcanic SO_2 reaches the stratosphere. There, the dry, cold and stratified atmosphere allows the sulfuric acid layers to remain in the atmosphere for years, slowly spreading an aerosols blanket around the globe. The tiny aerosols then act efficiently as reflectors and absorbers of the incoming solar radiations, significantly modifying the energy balance of the atmosphere (Kiehl and Briegleb, 1993) and the ocean (Gleckler et al., 2006; Miller et al., 2012; Ortega et al., 2015). With a lifetime of 2 to 4 years, these aerosols of sulfuric acid ultimately fall into the troposphere to reach the ground within weeks.

In Polar Regions, the deposition of the sulfuric acid particles on pristine snow will generate an acidic snow layer, enriched in sulfate. The continuous falling of snow, the absence of melting and the ice thickness make the polar snowpack the best records of the Earth's volcanic eruptions. Hammer (1977) was the first to recognize the polar ice propensity to record such volcanic history. Built on the seminal work of Hammer et al., a paleo-volcanism science developed around this discovery with twofold aims. The first relies on the idea that the ice record can reveal past volcanic activity and, to a greater extend, its impact on Earth's climate history (Robock, 2000; Timmreck, 2012). Indeed, at millennium time scale, volcanoes and the solar activity are the only two recognized natural climate forcings (Stocker et al., 2013). Based on ice records, many attempts are made to extract the climate forcing induced by a volcanic eruption (Crowley and Unterman, 2013 ; Gao et al., 2008, 2007; Sigl et al., 2013, 2014; Zielinski, 1995). However, such an approach is inevitably prone to large uncertainty pertaining to the quality of the ice record and non-linear effects between deposition fluxes and source emissions (Pfeiffer et al., 2006). The second aim of the paleo-volcanism is to provide an absolute dating scale when clear volcanic events in differently located ice cores can be unambiguously attributed to the same dated event (Severi et al., 2007). Per se, the time synchronization of different proxy records is possible, allowing studying the phasing response of different environmental parameters to a climate perturbation (Ortega et al., 2015; Sigl et al., 2015) or estimating the snow deposition over time (Parrenin et al., 2007). Whatever the intent is, the paleo-volcanism should rely on robust and statistically relevant ice core records.

To date a core or to establish a volcanic index, the work assumes a clear identification of a volcanic event, without any confusion with background variations induced by other sulfur sources (e.g. marine, anthropogenic, etc). Besides seasonal layer counting whenever possible, bi-polar comparison of ice sulfate records is the method of choice to establish an absolute dated volcanic index (Langway et al., 1988). Known or unknown events can both be used to synchronize different cores. However, only a limited number of peaks, with characteristic shape or intensity, and known to be associated with a dated eruption, can be used to set a reliable time scale (Parrenin et al., 2007). This restriction is partly fueled by the poor and/or unknown representativeness of most of the volcanic events found in ice cores. Most of the time, a single core is drilled at a given site and used for cross comparison with other sites, which is clearly insufficient for ambiguous events. At a large scale, sulfate deposition is highly variable in space and mainly associated with atmospheric transport and precipitation patterns. At a local scale (ca. 1 m), variability can emerge from post-deposition processes. While sulfate is a non-volatile species supposed to be well preserved in snow, spatial variability is induced by drifted snow, wind erosion leading to surface roughness heterogeneities (Libois et al., 2014). These effects are particularly amplified in low accumulation sites where most of the deep drilling sites are performed (EPICA-community-members, 2004; Jouzel, 2013; Lorius et al., 1985). To the best of our knowledge, one single study has used multiple drillings at a given site to analyze the representativeness of the ice core record (Wolff et al., 2005). This study took advantage of the two EPICA cores drilled at Dome C, 10 m apart (Antarctica, 75°06′ S, 123°21′ E, elevation 3220 m, mean annual temperature −54.5 °C) (EPICA-community-members, 2004) to compare the dielectric profile (DEP) along the 788 m common length of the two cores. For the two replicate cores, statistical analysis showed that up to 50 % variability in the pattern of any given peak was encountered as a consequence of the spatial variability of the snow deposition. The authors concluded that ice-core volcanic indices from single cores at such low-accumulation sites couldn't be reliable and what was required was a network of close-spaced records. However, as mentioned in Wolff's conclusion, this statistical study relied only on two records. Additionally, DEP signals are known to be less sensitive than sulfate signal for volcanic identification, and more accuracy is expected by comparing sulfate profiles. The authors thus encouraged conducting a similar study on multiple ice cores to see if the uncertainty could be reduced.

In the present study we took advantage of the drilling of 5 ice cores at Dome C, initially intended for the analysis of sulfur isotopes of the volcanic sulfate. Putting aside the number of records, our approach is similar in many points to Wolff's work. However, it has the advantage of relying on highly resolved sulfate profiles. In addition, the spatial scale is slightly smaller as the 5 cores were drilled 1 m apart. The comparison of 5 identically processed cores is a chance to approach the representativeness of a single core reconstruction at a low accumulation site, the most prone to spatial variability. Therefore new constrains on sulfate deposition variability induced by spatial heterogeneity in such sites is expected from the present work. Even if recent publications (Sigl et al., 2014), underline the need of using multiple records in low accumulation sites, to overcome the spatial variability issue, such records are not always available. This lack of records adds uncertainty in the volcanic flux reconstruction based on polar depositional pattern. Our study should help to better constrain the error associated with local scale variability, and ultimately, the statistical significance of volcanic reconstructions. The present study discusses the depth shift, occurrence of events and deposition flux variability observed in the 5 core drilled.

2 Experimental setup and methods

2.1 Core drilling

The project "VolSol", initiated in 2009, aimed at constraining the estimation of the natural part of radiative forcing, composed of both volcanic and solar contributions using ice core records of sulfate and Beryllium-10. In order to build a robust volcanic index including a discrimination of stratospheric events based on sulfur isotopic ratios (Baroni et al., 2008; Savarino et al., 2003), 5 × 100 m-firn cores (dia. 10 cm) were drilled in 2010/11 at 1 m away from each other. The drilling took place at the French-Italian station Concordia (Dome C, Antarctica, 75°06′ S, 123°21′ E, elevation 3220 m, mean annual temperature −54.5 °C) where the mean annual snow accumulation rate is about $25\,\mathrm{kg\,m^{-2}\,y^{-1}}$, leading to an estimated time-period covered by the cores of 2500 years. Cores were logged and bagged in the field, and temporarily stored in the underground core buffer (−50 °C) before analysis. The unusual number of ice core drilled at the same place was driven by the amount of sulfate necessary to conduct the isotopic analysis. However, this number of replicate cores drilled 1 m apart offers the opportunity to question the representativeness of a volcanic signal extracted from a single core per site.

2.2 Sampling, resolution and IC analyses

Analyses were directly performed on the field during two consecutive summer campaigns. Thirty meters were analyzed in 2011, the rest was processed the following year. The protocol was identical for each core and the steps followed were:

- Decontamination of the external layer by scalpel scrapping
- Longitudinal cut with a band saw of a 2 cm stick of the most external layer
- Sampling of the ice stick at a 2 cm-resolution (ca. 23 600 samples)

- Thawing the samples in 50 mL centrifuge tubes, and transfer in 15 mL centrifuge tubes positioned in an autosampler
- Automatic analysis with a Metrohm IC 850 in suppressed mode (NaOH at 7 mM, suppressor H_2SO_4 at 50 mM, Dionex AG11 column), in a fast IC configuration (2 min run) with regular calibration (every 60 samples) using certified sulfate reference solution (Fisher brand, 1000 ppm certified).

Due to the fragility of snow cores, the first 4 m were only analyzed on a single core (Fig. 1). We will thus not discuss the variability of the Pinatubo and Agung eruptions present in these first 4 m.

2.3 Peaks discrimination method

As with most algorithms used for peak detection, the principle is to detect anomalous sulfate concentration peaks from a background noise (stationary or not), which could potentially indicate a volcanic event. The estimation of the background value should therefore be as accurate as possible. Using core 2 as our reference core, we observed a background average value stationary and close to 85 ± 30 ppb (1σ) at Dome C during the 2500 years of the record. However, the variability is sufficient enough to induce potential confusion on small peaks detection. Therefore, a stringent algorithm using PYTHON language (accessible on demand) was developed to isolate each possible peak. The algorithm treats the full ice record by 1 m section (ca. 45–50 samples). For each meter, a mean concentration (m) and standard deviation (σ) is calculated regardless of the presence or not of peaks in the section. Then, every value above the $m+2\sigma$ is removed from the 1 m dataset. A new mean and standard deviation is calculated and the same filtration is applied. Iteration runs until no more data above $m+2\sigma$ is found. At that point, m represents the background mean concentration. The process runs for each 1 m section, starting from the surface sample and until the end of the core. Then, each 1 m dataset is shifted by one sample; the process is reset and the peak detection run again on each new 1 m dataset. Sample shift is applied until the last sample of the first 1 m section is reached so that no bias is introduced by the sampling scheme. Every concentration data point is thus compared approximately with its 100 neighbor data (50 of each side). Each data point isolated by the algorithm is further tested. To be considered as a point belonging to a potential volcanic peak, the data should be detected in a given core (i.e. for being above the $m + 2\sigma$ final threshold) in at least 50 % of the 50 runs. Additionally, the point has to be part of at least three consecutive points passing the same 50 % threshold detection. This algorithm was applied individually on each core, giving 5 different lists of peak. In total, 54, 51, 47, 50, 47 peaks were detected on core 1, 2, 3, 4 and 5, respectively.

2.4 Cores synchronization and dating

Core 1 was entirely dated with respect to the recently published volcanic ice core database (Sigl et al., 2015) using *Analyseries* 2.0.8 software (http://www.lsce.ipsl.fr/Phocea/Page/index.php?id=3), and covers the time period of −588 to 2010 CE. Figure 2 shows the age-depth profile obtained for this core. A total of 13 major volcanic eruptions well dated were used as time markers to set a time scale (bold date in Table 1). Core 1 was entirely dated through linear interpolation between those tie points. Dated core 1 was then used as a reference to synchronize the remaining 4 cores, using the same tie points and 10 additional peaks (non-bold date in Table 1), presenting characteristic patterns common to each core. In total, 23 points were therefore used to synchronize the cores.

2.5 Composite building from the 5 ice cores

Through the routine described above, the five cores are depth-synchronized using the 23 tie points and other potential volcanic events in each core cores are detected independently. Therefore, the number of peaks detected in each core is different (between 47 and 54) and their depth (with the exception of the tie points used) is slightly different

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to each other cores due to sampling scheme and position of the maximum concentration.

For clarity, let $P_{i,j}^{k}$ describes the jth peaks detected in core i with k, the number of occurrence of $P_{i,j}$ in the five P_i cores ($1 \leq k \leq 5$). Therefore, $P_{i,j}^{k}$ describes the number of k time, the peak j in core i has been found in the five cores. The goal of the algorithm (written in PYTHON) is to build a single composite global volcanic record, $\mathbf{P} = P_{j'}^{k} = \sum\limits_{i} P_{i,j}^{1} - \sum\limits_{i}^{k-1} P_{i,j}^{k}$, composite of the 5 cores, through the following routine. Peaks detected in the core 1 (defined by the depth and value of their maximum concentration) are used to set the initial composite record. At the beginning of the routine, $P_{j}^{k} = P_{1,j}^{1}$, the composite record is composed of the j peaks detected in core 1 with an occurrence of 1 for each. Then, each peak listed in core 2, $P_{2,j}^{1}$, is compared to the composite series $\mathbf{P} = P_{1,j}^{1}$. Sulfate peak $P_{2,j}^{1}$ is associated to the same event of $\mathbf{P}$ if their respective depths are within ±20 cm depth tolerance. This level of tolerance is consistent with the dispersion in width and shape observed on peaks introduced by the sampling resolution (ca. 2 cm), spatial variability, and snow compaction (see Fig. 3a and b for two basic situations). For each common occurrence, k is incremented. The process goes on until the five cores are compared. At the end of the process, $\mathbf{P}$ contains the number of common and single peaks detected and their occurrence k (Fig. 4).

3 Results and discussions

3.1 Depth offset between cores

Depth offsets between cores are the result of the surface roughness at the time of drilling, variability in snow accumulation, heterogeneous compaction during the burying of snow layers and logging uncertainty. This aspect has been discussed previously, over a similar time-scale (Wolff et al., 2005), and over a longer time-scale (Barnes et al., 2006) in Dome C. Surface roughness, attributed to wind speed, temperatures and accumulation rate, is highly variable in time and space. These small features hardly contribute to the depth offset on a larger spatial scale, in which case glacial flow can control the offset between synchronized peaks, as it seems to be the case in South pole site (Bay et al., 2010). However, in Dome C, and at the very local spatial scale we are considering in the present work, roughness is significant regarding to the accumulation rate. It is therefore expected that synchronized peaks should be found at different depths. The offset trend fluctuates with depth, due to a variable wind speed (Barnes et al., 2006). To estimate the variability in the depth shift for identical volcanic events, we used the tie points listed in Table 1. For each peak maximum, we evaluate the depth offset of core 1, 3, 4 and 5, with respect to core 2. To avoid logging uncertainty due to poor snow compaction in the first meters of the cores and surface roughness at the time of the drilling, we used the UE 1809 depth in core 2 (13.30 m) as a depth reference horizon from which all other depth cores were anchored using the same 1809 event. For this reason, only eruptions prior to 1809 were used to evaluate the offset variability, that is 18 eruptions instead of the 23 used for the cores synchronization. Figure 5, shows the distribution of depth shift of the cores with respect to core 2. While the first 40 m appear to be stochastic in nature, a feature consistent with the random local accumulation variations associated with snow drift in Dome C site, it is surprising that at greater depth, offset increases (note that the positive or negative trends are purely arbitrary and depends only on the reference used, here core 2). The maximum offset, obtained between core 3 and 5 is about 40 cm. Such accrued offsets with depth were also observed by Wolff et al. (2005) and were attributed to the process of logging despite the stringent guidelines used during EPICA drilling. Similarly, discontinuities in the depth offset, observed by Barnes et al. (2006) were interpreted as resulting from logging errors. As no physical processes can explain a trend in the offsets, we should also admit that the accrued offset is certainly the result of the logging process. In the field, different operators were involved but a common procedure was used for the logging. Two successive cores extracted from the drill were reassembled on a bench to match the non uniform drill cut and then hand sawed meter by meter to get the best precise depth core, as neither the drill depth recorder nor the length of the drilled core section can be used for establishing the depth scale. This methodology involving different operators should have randomized systematic errors but obviously this was not the case. Despite the systematic depth offset observed, synchronization did not pose fundamental issues as the maximum offset in rescaled profiles never exceeds the peak width (ca. 20 cm) thank to the 10 possible comparisons when pair of core are compared. Confusion or missing events are thus very limited in our analysis (see next section).

3.2 Variability in events occurrence

The variability in events occurrence in the 5 ice cores has been evaluated through the construction of a composite record (Fig. 4) and the counting of events in each core as described in the method. By combining the five ice cores, we listed a total amount of 91 sulfate peaks (Pinatubo and Agung not included), which are not necessarily from volcanic sources. Some peaks can be due to post deposition effects affecting the background deposition, or even contamination. When it comes to defining a robust volcanic index, peak detection issues emerge. Chances to misinterpret a sulfate peak and assign it, by mistake, to a volcanic eruption, as well as chances to miss a volcanic peak, can be discussed through a statistic analysis conducted on our five cores.

We try to evaluate to what extend multiple cores comparison facilitates the identification of volcanic peaks, among all sulfate peaks that can be detected in a core. To do so, we assumed that a peak is of volcanic origin as soon as it is detected at least in two cores. In other words, the probability to have two non-volcanic peaks synchronized in two different cores is nil. It is expected that combining an increasing number of cores will increasingly reveal the real pattern of the volcanic events. All possible combinations from 2 to 5 cores comparison were analyzed, totalizing 26 possibilities for the entire population. The results for each comparison were averaged, giving a statistic on the average number of volcanic peaks identified per number of cores compared.

The results of the statistical analysis are presented in Fig. 6. As expected, in a composite made of 1 to 5 cores, the number of sulfate peaks identified as volcanic peaks (for being detected at least twice) increases with the number of cores combined in the composite. Thus, while only 30 peaks can be identified as volcanic from a two cores study, a study based on 5 cores can yields 62 such peaks. The 5-cores comparison results in the composite profile given in Fig. 4a. The initial composite of 93 peaks is reduced to 64 volcanic peaks (Pinatubo and Agung included) after removing the single peaks (Fig. 4b). Each characteristic of the retained peaks is given in Table 2. The main conclusion observing the final composite record is that only 17 of the 64 peaks were detected in all of the 5 cores and 68 % of all peaks were at least present in two cores. At the other side of the spectrum, 2-cores analysis reveals that only 33 % (30 peaks on average) of the peaks are identified as possible eruptions. Two cores comparison presents still a high risk of not extracting the most robust volcanic profile at low accumulation sites, a conclusion similar to Wolff et al. (2005). Surprisingly, it can also be noticed that 5-cores comparison does not results in an asymptotic ratio of identified volcanic peaks, suggesting that 5 cores are not sufficient either to produce a steady state picture. High accumulation sites should be prone to less uncertainty; however, this conclusion remains an a priori that still requires a confirmation.

Large and small events are not equally concerned by those statistics. Figure 7 shows that the probability of presence is highly dependent on peak flux and the chance to miss a small peak (maximum flux in the window $[f+2\sigma : f+5\sigma]$, f being the background average flux) is much higher than the chance to miss a large one (maximum flux above $f+8\sigma$). However, it is worth noticing that major eruptions can also be missing from the record, as it has already been observed in other studies (Castellano et al., 2005; Delmas et al., 1992). The most obvious example in our case is the Tambora peak (1815 AD), absent in 2 of our 5 drillings, while presenting an intermediate to strong signal in the others (Fig. 8). The reason for the variability in event occurrence has been discussed already by Castellano et al. (2005). In the present case of close drillings, long-range transport and large-scale meteorological conditions can be disregarded due to the small spatial scale of our study; the snow drift and surface roughness is certainly the main reasons for missing peaks. The fact that two close events as UE 1809 and Tambora are so differently recorded indicates how punctual, in time and space post-depositional effects can affect the recording of eruptions.

3.3 Variability in signal strength

To compare peak height variability, detected peaks were corrected by subtracting the background from peak maximum. We considered C_i/C_{mean} variations, C_i being the SO_4^{2-} maximum concentration in core i (1 to 5), and C_{mean} being the mean of those concentration for the event i. For concentration values, positive by definition, the log-normal distribution is more appropriate; geometric means and geometric standard deviations were used, as described by Wolff et al. (2005) (Table 3). In our calculation, the geometric standard deviation based on 2 cores is 1.37; in other words, maximum concentrations are uncertain by a factor 1.37. This factor is slightly lower than the one obtained in Wolff et al. (2005) (1.5). Our cores are drilled closer (one meter from each others, instead of 10 m for Wolff et al.), which might slightly reduce the uncertainty. The peaks height variability obtained by averaging 5 cores (1.21), matches Wolff et al. forecast. Based on a 50 % uncertainty on 2 cores, Wolff et al. predicted a 20 % uncertainty on a 5 cores study (consistent with a reduction of the standard deviation by a factor of $1/\sqrt{n}$, by averaging n values). Comparing the peaks maximums enables us to compare our study with Wolff's study, also based on peaks maximums. However, in our case, comparing maximums induces a bias related to the sampling method: with a two centimeters resolution on average, peak's height is directly impacted by the cutting, which tends to smooth the maximums. Comparing the total sulfate deposited during the event is more appropriate. Proceeding on a similar approach, but reasoning on mass of deposited sulfate rather than maximum concentration, the obtained variability is higher than previously: 42 % uncertainty on volcanic deposited sulfate mass, on a 5-cores study (F_i/F_{mean}, F_i being the mass flux of peak i), and 61 % uncertainty on a 2-cores comparison (F_i/F_1). The difference in the signal dispersion between the two approaches rests on the fact that peak maximum has a tendency to smooth the concentration profile as a consequence of the sampling strategy. This artifact is suppressed when the total mass deposited is considered. In any case, uncertainty seems to be significantly reduced when comparing 5 cores instead of 2.

4 Conclusions

This study confirms in many ways previous work on multiple drilling variability (Wolff et al., 2005). As already discussed, peaks flux uncertainty can be significantly reduced (60 to 40 %) by averaging 5 ice-cores signals instead of 2. A 5-cores composite profile has been built using the criteria that a peak is considered as volcanic if present at least in two cores. We observed that the number of volcanic peaks listed in a composite profile increases with the number of cores considered. With 2 cores, only 33 % of the peaks present in the composite profile are tagged as volcanoes. This percentage increases to 68 % with 5 cores. However, we did not observe an asymptotic value, even with 5 cores drilled. A record based on a single record in a low accumulation site is therefore very unlikely to be a robust volcanic record. Of course, peaks presenting the largest flux are more likely to be detected in any drilling, but the example of the Tambora shows that surface topography is variable enough to erase even the most significant signal, although rarely. This variability in snow surface is evidenced in the depth offset between two cores drilled less than 5 m from each other, as peaks can easily be situated 40 cm apart.

In low accumulation sites such as Dome C, where surface roughness can be on the order of the snow accumulation and highly variable, indices based on chemical records should be considered with respect to the time-scale of the proxy studied. Large time-scale trends are faintly sensitive to this effect. On the contrary, a study on episodic events like volcanic eruptions or biomass burning, with a deposition time in the order of magnitude of the surface variability scale should be based on a multiple-drilling analysis. A network of several cores is needed to obtain a representative record, at least in terms of recorded events. However, although lowered by the number of cores, the flux remains highly variable, and still uncertain by a factor of 1.4 with 5 cores. This point is particularly critical in volcanic reconstructions that rely on the deposited flux to estimate the mass of aerosols loaded in the stratosphere, and to a larger extend, the climatic forcing induced. Recent reconstructions largely take into account flux variability associated with regional pattern of deposition, but this study underlines the necessity of not neglecting local scale variability in low accumulation sites. Less variability is expected with higher accumulation rate, but this still has to be demonstrated. Sulfate flux is clearly one of the indicators of the eruption strength, but due to transport, deposition and post-deposition effects, such direct link should not be taken for granted.

With such statistical analysis performed systematically at other sites, we should be able to reveal even the smallest imprinted volcanoes in ice cores, extending the absolute ice core dating, the teleconnection between climate and volcanic events and improving the time-resolution of mass balance calculation of ice sheets.

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Table 1. Tie points used to set the time scale and synchronize the cores. Volcanic events are named "Ev x" if they are not assigned to a well-known eruption. Dating of the events is based on Sigl et al. (2015).

Eruption	core 1	core 2	core 3	core 4	core 5	date of deposition
Surface	0	0	0	0	0	2010
Pinatubo	1.53					**1992**
Krakatoa	8.82	8.92	8.67	8.71	8.63	1884
Cosiguina	11.98	11.83	11.65	11.62	11.46	1835
Tambora	12.85			12.6	12.57	**1816**
UE 1809	13.33	13.3	13.04	13.08	12.98	**1809**
ev 7	15.98	15.93	15.66	15.67	15.52	1762
Serua/UE	19.29	19.22	18.93	18.94	18.78	**1695**
UE 1621	21.87	21.74	21.53	21.48	21.4	1621
kuwae	30.18	30.04	29.92	29.85	29.73	**1459**
ev 16 – A	37.35	37.29	37.17	37.04	36.91	1286
ev 16 – B	37.77	37.77	37.62	37.52	37.4	**1276**
ev 16 – C	38.1	38.04		37.78		1271
Samalas	38.49	38.46	38.28	38.2	38.09	**1259**
ev 17	39.59	39.56	39.46	39.36	39.2	**1230**
ev 18	41.87	41.83	41.7	41.6	41.41	**1172**
ev 22	50.26	50.3	50.2	50.11	49.87	953
ev 27	60.77	60.72	60.66		60.27	**682**
ev 31	65.72	65.74	65.68	65.6	65.25	**542**
ev 35	76.06	76.13	76	75.94	75.64	240
ev 46	90.42	90.53	90.36	90.41	89.95	**−207**
ev 49	97.15	97.16	97.19	97.22	96.74	**−427**
ev 51	100.16	100.19		100.22	99.7	−525

Table 2. Sulfate peaks (maximum concentration and mass of sulfate deposited) considered as volcanic eruptions based on the statistical analysis of the 5 cores. The flux is calculated by integrating the peak, assuming a constant snow accumulation of 25 kg m^{-2} y^{-1} and using the density profile obtained during the logging process. Flux values are corrected from background sulfate. 0 stands for non-detected events in the cores. Agung (3.77 m) and Pinatubo (1.52 m) were not included in the statistical analysis because they were analyzed only in core 1, and thus are marked as not applicable (n/a).

Peak depth (m)	date (year)	core 1		core 2		core 3		core 4		core 5	
		[SO_4^{2-}] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO_4^{2-}] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO_4^{2-}] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO_4^{2-}] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO_4^{2-}] (ng g^{-1})	Volcanic flux (kg-S km^{-2})
1.52	1992	188	2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
3.77	1964	207	2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
6.24	1922	0	0	164	1	0	0	132	1	0	0
8.59	1889	0	0	0	0	0	0	134	0	117	0
8.92	1884	232	3	262	3	236	3	240	2	216	2
11.83	1827	220	3	173	2	190	1	177	1	173	1
12.08	1821	0	0	0	0	144	1	0	0	137	0
12.91	1815	455	4	0	0	0	0	188	1	307	2
13.3	1809	436	5	291	3	392	4	408	1	461	4
15.93	1747	176	1	248	2	201	1	0	0	0	0
19.29	1681	287	4	0	0	168	2	194	1	0	0
20.3	1661	261	3	0	0	0	0	196	1	178	1
20.7	1650	0	0	0	0	0	0	123	1	149	1
21.74	1628	257	3	249	3	259	4	282	2	257	4
22.72	1608	181	2	146	1	141	1	0	0	0	0
23.77	1588	225	4	0	0	170	1	0	0	0	0
25.78	1544	144	2	0	0	0	0	148	1	0	0
30	1459	496	10	442	9	422	9	543	2	559	12
30.56	1450	0	0	143	1	131	1	0	0	0	0
31.83	1408	0	0	0	0	0	0	155	1	148	1
33.51	1370	0	0	0	0	140	1	0	0	162	2
34.85	1339	273	4	288	4	209	2	303	3	269	4
37.29	1282	325	6	324	5	373	6	347	2	458	10
37.77	1276	563	9	605	12	570	10	525	2	497	7
38.04	1264	205	1	180	1	0	0	235	1	0	0
38.46	1259	1086	17	1022	18	928	17	1030	3	1428	30
39.25	1236	0	0	0	0	132	1	147	1	151	1
39.56	1228	268	5	260	5	279	4	315	3	320	5
41.17	1189	0	0	216	1	247	4	0	0	241	3
41.83	1173	437	9	401	9	377	8	378	3	433	10
44.4	1111	186	2	0	0	243	2	225	2	195	2
44.87	1098	174	1	0	0	0	0	153	1	0	0

Table 2. Continued.

Peak depth (m)	date (year)	core 1		core 2		core 3		core 4		core 5	
		[SO$_4^{2-}$] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO$_4^{2-}$] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO$_4^{2-}$] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO$_4^{2-}$] (ng g^{-1})	Volcanic flux (kg-S km^{-2})	[SO$_4^{2-}$] (ng g^{-1})	Volcanic flux (kg-S km^{-2})
45.81	1075	129	1	144	1	0	0	0	0	0	0
47.15	1041	187	1	193	1	217	2	0	0	203	2
47.5	1033	192	2	163	1	166	1	0	0	198	2
48	1020	0	0	155	1	168	1	0	0	0	0
49.63	977	132	1	0	0	139	1	0	0	0	0
50.3	961	209	3	256	5	236	4	220	2	227	4
52.49	904	254	1	0	0	215	1	184	1	233	3
54.35	855	0	0	0	0	0	0	155	1	249	4
55.65	821	184	3	193	2	191	2	181	2	249	2
58.26	750	155	1	202	1	0	0	201	2	0	0
60.72	688	287	4	216	6	243	3	0	0	230	3
64.49	592	528	11	0	9	430	8	367	2	393	7
65.74	578	287	6	274	4	283	6	306	3	304	6
68.41	490	132	1	0	0	182	1	0	0	0	0
69.41	465	194	3	168	1	0	0	207	2	233	3
72.38	350	0	0	172	2	203	2	0	0	188	2
73.13	328	0	0	169	2	152	1	0	0	0	0
73.95	304	0	0	0	0	171	1	190	2	0	0
76.13	216	205	4	258	6	237	7	287	3	262	5
77.17	169	179	2	206	5	211	4	219	3	272	5
78.31	121	250	5	0	0	156	1	203	1	219	3
79.98	80	165	2	187	1	0	0	162	1	167	3
84.5	−28	202	3	199	3	222	4	0	2	188	3
85.44	−50	0	0	155	1	0	0	0	0	240	3
87.89	−129	236	4	212	0	270	5	244	3	0	0
89.28	−174	0	0	0	0	0	0	190	1	164	1
90.53	−207	276	6	286	8	278	7	296	2	241	2
91.72	−253	0	0	0	0	0	0	227	2	244	5
94.83	−356	0	0	228	2	198	2	216	2	0	0
97.16	−426	331	6		0	403	9	436	5	675	21
97.31	−439	0	0	131	5	0	0	0	0	0	0
100.19	−526	219	4	224	2	0	0	247	3	235	3

Table 3. Statistics on sulfate signal for identical peaks in core 1, 2, 3, 4 and 5. Geometric standard deviations are calculated on peaks heights (i.e. maximum concentration reached, in ng g^{-1}) and on peaks sulfate flux (i.e. total mass of volcanic sulfate deposited after the eruption). Background corrections are based on an average concentration value of $85\,\text{ng g}^{-1}$.

Study	Number of compared cores	Geom. std deviation based on maximum concentration	Geom std deviation based on deposition flux
Wolff and others	2	1.5	
This study	2*	1.37	1.61
This study	5	1.21	1.42

* C_x/C_1 with $x = 2,3,4,5$.

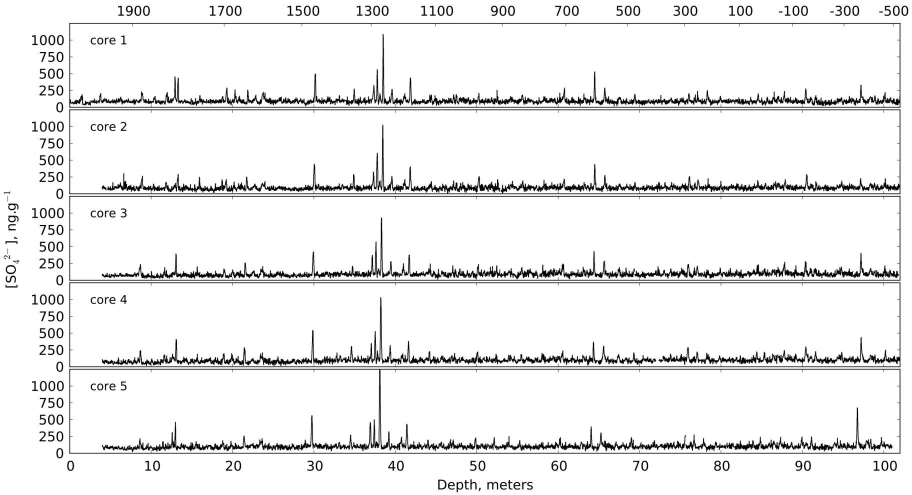

Figure 1. Sulfate profiles of the 5 replicate cores obtained during a drilling operation at Dome C – Antarctica, in 2011.

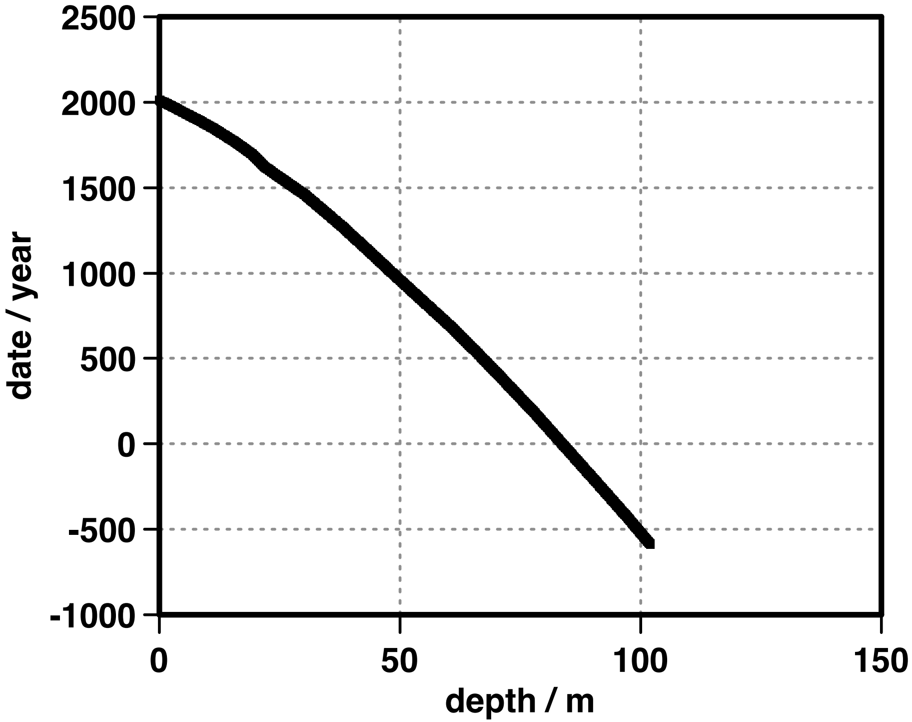

Figure 2. Age vs. depth in core 1, drilled in 2011 CE, Dome C – Antarctica.

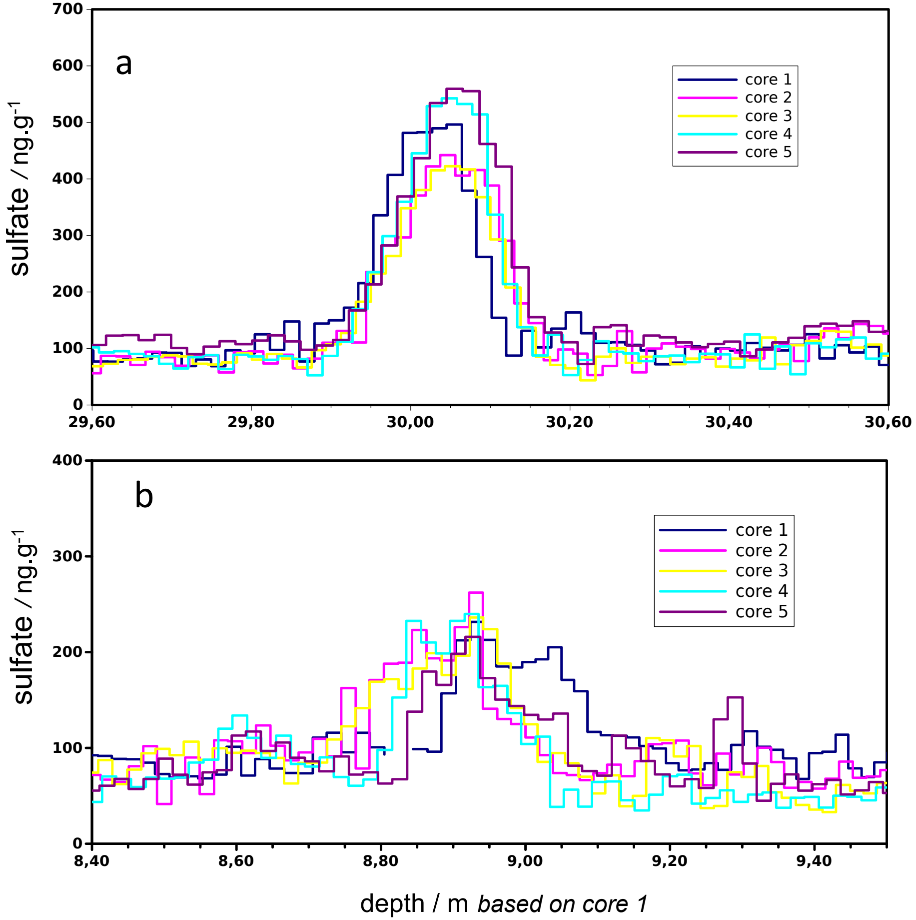

Figure 3. Kuwae (**a**, top) and Krakatoa (**b**, bottom) sulfate concentration profiles after depth synchronization. All peaks are within a 20 cm uncertainty, enabling to clearly attribute each occurrence to a single event.

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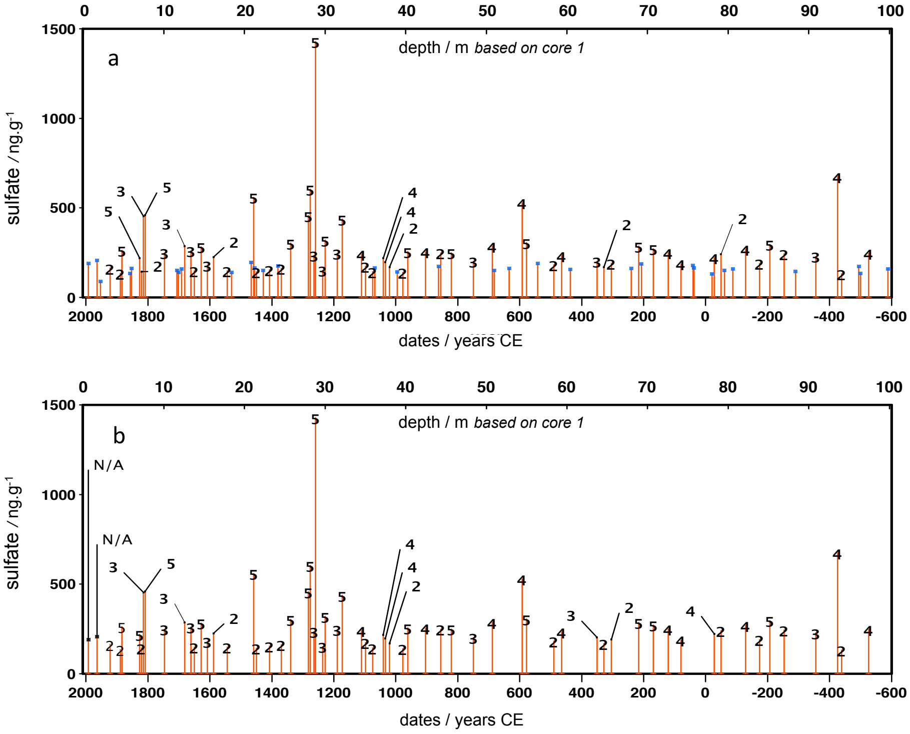

Figure 4. (a) Composite sulfate peak profile deduced from our statistical analysis of the 5 cores using our detection peak and synchronization algorithms (see text). The numbers indicate the number of time a common peak is found in the cores. Unnumbered peaks are peaks found in a single core. **(b)** Same as **(a)** without the single detected peaks. All the remaining peaks are considered as volcanic eruptions. See Table 2 for details.

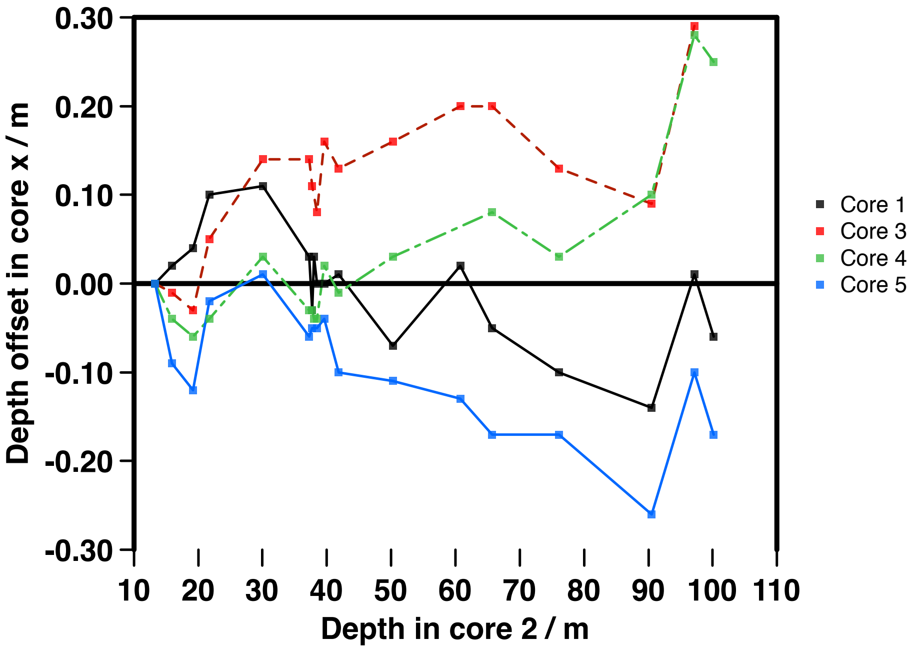

Figure 5. Depth offset of 18 common and well-identified volcanic events in cores 1, 3, 4 and 5 relatively to core 2. To overcome the offset due to the drilling process and poor core quality on the first meters, UE 1809 (depth ca. 13 m) is taken as the origin and horizon reference.

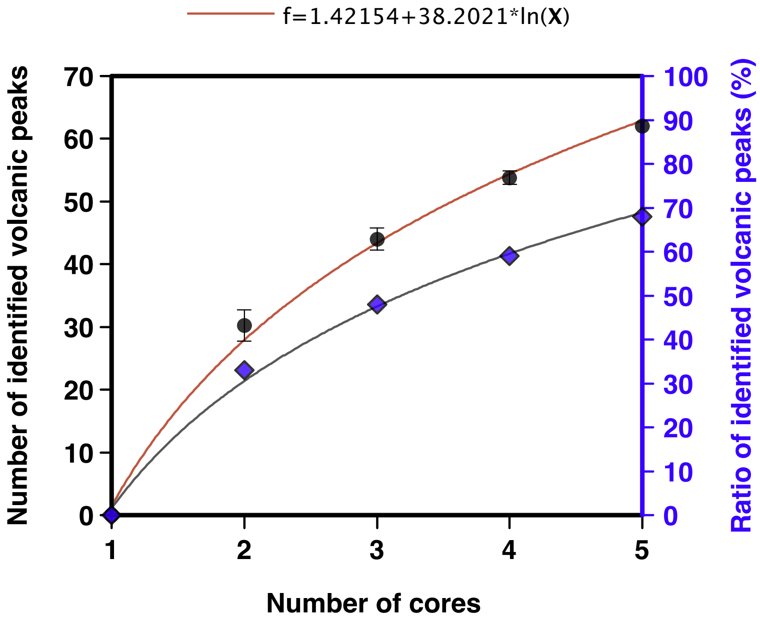

Figure 6. Black dots (left axis) represent the number of sulfate peaks that can be identified as volcanic peaks in a composite profile, made of *n* cores (with *n* ranging from 1 to 5). A sulfate peak appearing simultaneously in at least two cores is considered to be a volcanic peak. As evidenced, the number of volcanic events in a composite increases with the number of contributing cores, with a progression well fitted by a logarithmic relation. Blue diamonds represent the ratio of identified volcanic peaks, i.e. the number of identified volcanic peaks (plotted on the left axis), relatively to the total number of sulfate peaks (no discrimination criteria) in a composite made of 5 cores. In our case, the 5 ice-cores composite comprises 91 sulfate peaks (Agung and Pinatubo excluded). With two cores, only 33 % of them would be identified as being volcanic peaks (detected in both cores), while 68 % of them can be identified as volcanic events using 5 cores.

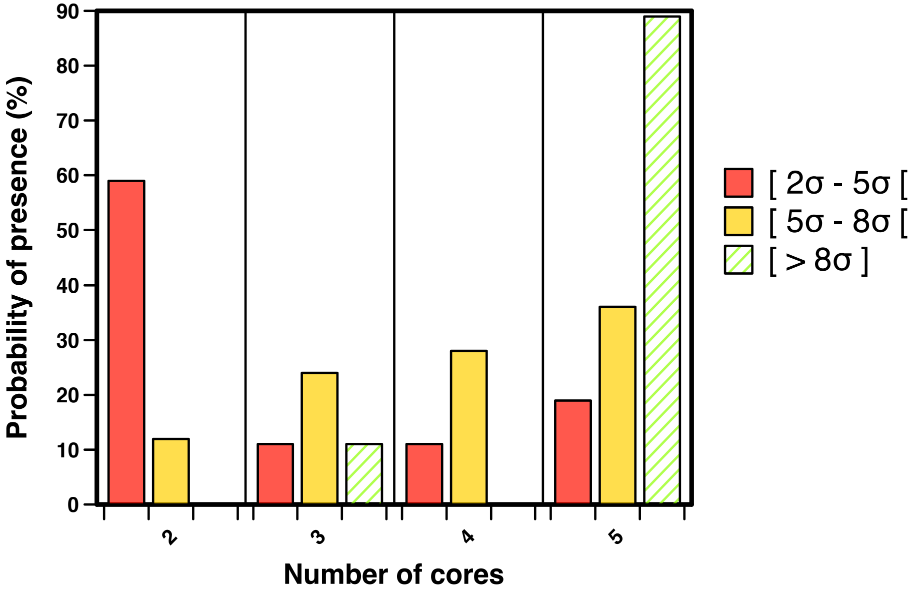

Figure 7. Peaks probability to be detected in 2, 3, 4 or 5 cores, as function of their flux. The three categories of flux are defined by peaks flux value, relatively to the average flux, and quantified by *n* time (2, 5 and 8) the flux standard deviation, calculated for a 30 ppb standard deviation in concentrations.

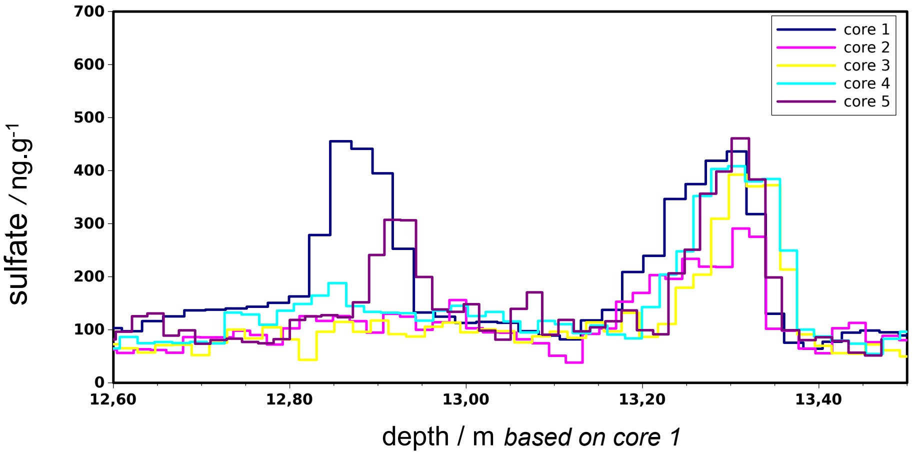

Figure 8. Close look at UE 1809 and Tambora (1815) events showing the absence of the Tambora event in 3 out of the 5 cores. This figure illustrates the possibility of missing major volcanic eruptions when a single core is used.