The Icelandic Laki volcanic tephra layer in the Lomonosovfonna ice core, Svalbard

Teija Kekonen, John Moore, Paavo Perämäki & Tõnu Martma

The largest sulphuric acid event revealed in an ice core from the Lomonosovfonna ice cap, Svalbard, is associated with the densest concentration of microparticles in the ice core at 66.99 m depth. Electron microscope analysis of a volcanic ash particle shows it has the same chemical composition as reported for debris from the eruption of Iceland's Laki fissure in 1783 and confirms the identification of the tephra. Most of the particles in the deposit are not ash, but are common sand particles carried aloft during the eruption event and deposited relatively nearby and downwind of the long-lasting eruption. The tephra layer was found 10 - 20 cm deeper than high sulphate concentrations, so it can be inferred that tephra arrived to Lomonosovfonna about 6 - 12 months earlier than gaseous sulphuric acid precipitation. The sulphuric acid spike has a significant cooling impact recorded in the oxygen isotope profile from the core, which corresponds to a sudden drop in temperature of about 2 °C which took several years to recover to previous levels. These data are the first particle analyses of Laki tephra from Svalbard and confirm the identification of the large acidic signal seen in other ice cores from the region. They also confirm the very large impact that this Icelandic eruption, specifically the sulphuric acid rather than ash, had on regional temperatures.

T. Kekonen, University of Oulu, Box 3000, FI-90014 University of Oulu, Finland and Arctic Centre, University of Lapland, Box 122, FI-96101 Rovaniemi, Finland, teija.kekonen@oulu.fi; J. Moore, Arctic Centre, University of Lapland, Box 122, FI-96101 Rovaniemi, Finland; P. Perämäki, Dept. of Chemistry, University of Oulu, Box 3000, FI-90014 University of Oulu, Finland; T. Martma, Institute of Geology, Tallinn University of Technology, Estonia pst 7, EE-10143 Tallinn, Estonia.

Volcanic ash particles are commonly detected from ice cores because of their importance for dating (e.g. Grönvold et al. 1995; Zielinski et al. 1997). Volcanic eruptions usually produce large volumes of SO_2 gas, dust, lava, ash and rock (Thordarson et al. 2001). Volcanic material can travel high into the atmosphere and mix with air masses, which can spread very widely. This material is eventually scavenged in precipitation, or deposited dry in very arid regions.

Volcanic tephra includes all rock and lava particles that are erupted into the air, regardless of particle size. In addition to volcanic ash particles, tephra contains other larger sand and rock particles. Ash and other small particles can travel long distances, but bigger sand particles are much heavier than ash and are deposited much closer to the eruption site. Volcanic ash is the smallest tephra fragment (<2 mm) composed of silicon, aluminium, iron, calcium, magnesium, sodium and other trace elements. Each volcanic eruption produces volcanic ash particles with a specific signature in these elements, thereby producing a chemical fingerprint by which it can be identified

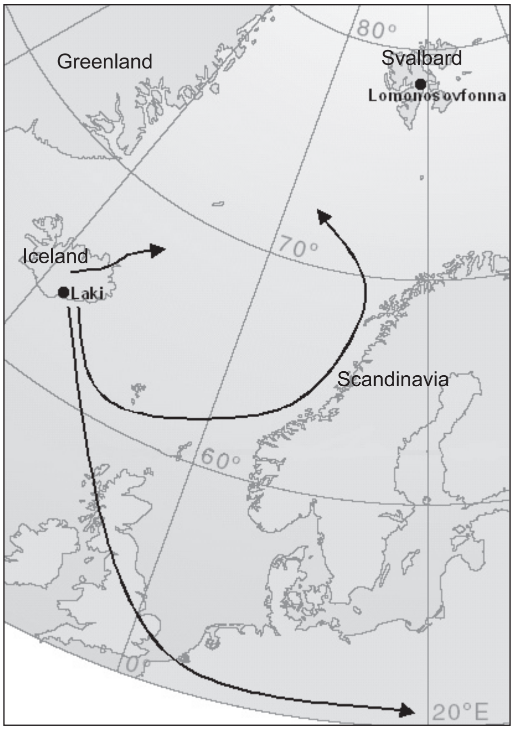

Fig 1. Map showing Svalbard and Iceland and the inferred plume direction of the westerly jet stream on 10 June 1783. Transport paths are based on the data of Thordarson & Self (2003) and Fiacco et al. (1994).

(e.g. Palais et al. 1992; Grönvold et al. 1995; Zielinski et al. 1997; Zielinski et al. 1998).

The eruption of Iceland's Laki fracture in 1783 was one of largest basaltic fissure eruptions in recorded history. The volume of aerosols injected into the atmosphere by the eruption was one of the greatest atmospheric pollution events over Europe during historic times (Thordarson & Self 2003). The Laki volcanic eruption lasted for eight months (June 1783 to February 1784) and produced one of the largest recorded basaltic lava flows in Iceland. The sulphuric and, especially, the hydrofluoric acid produced by the eruption were responsible for the deaths of more than half the animals on Iceland (Thordarson & Hoskuldsson 2002). There were also widespread effects in the Northern Hemisphere, including cooling (Thordarson & Hoskuldsson 2002; Highwood & Stevenson 2003; Thordarson & Self 2003).

A strong sulphate acid signal corresponding to an age of 1783–84 has been reported in many ice cores from Greenland and Svalbard (Fiacco et al. 1994; Zielinski et al. 1994; Thordarson et al. 1996; Watanabe et al. 2001; Thordarson & Self 2003).

In this work we have analysed samples close to a major sulphate peak in the ice core and found a particle-rich layer at a depth of 66.99 m using SEM-EDS. This is the first published result relating to the tephra layer and volcanic ash particle from the Laki eruption located in Svalbard glaciers.

Study site and methods

The 121 m long ice core was recovered with an electromechanical drill from the summit of the Lomonosovfonna ice cap (1255 m a.s.l.), on the island of Spitsbergen, Svalbard, in 1997 (Fig. 1) (Isaksson et al. 2001). Total ice depth from radar sounding was 123 m, and the site is close to the highest point of the ice cap with roughly radial ice flow. The ice core represents an approximately 800 year period. The time scale of the core was based on an ice layer thinning model (Nye 1963) tied with the known dates of prominent reference horizons (1963 radioactive layer and 1783 Laki volcanic sulphate layer and volcanic ash particle; see Kekonen et al. [2005] for details). The accumulation rate for the 1997–1963 period is 0.41 m water equivalent per year and a somewhat lower value of 0.31 m w.e. per year for the period 1963–1783. The model age profile can be independently checked by comparison with automated seasonal cycle counting in stable isotopes and ions down to 81 m (Pohjola et al. 2002). The model age at 81 m depth is 1705, while the cycle counting method gives a date of 1715. There is a thus a discrepancy of 10 years in about 75 years between the Laki horizon and the limit of cycle counting. However, the cycle counting method will always tend to miss a fraction of low accumulation rate years due to the resolution of the data and isotope diffusion effects, so a good model dating should be more reliable (on average) than cycle counting.

The current annual temperature range is from 0 °C to about –40 °C. Any summer meltwater is refrozen mostly within the previous winter's snow, and the remainder within the next two or three lower annual layers. Although percolation can be up to eight years in the warmest years in the 20th century, it was much reduced during the Little Ice Age (Kekonen et al. 2005). Various statistical analytical methods (see Kekonen et al. 2005; Moore et al. 2005) show that chemical and isotopic stratigraphy are sufficiently well preserved that significant decadal-scale periodicities can be found, annual layers can be counted for about 300 years, and changes in chemical composition related to changes in climate are far more significant than changes in chemical composition in ice layers subject to various degrees of percolation.

The core was transported and stored in a frozen state (–22 °C). The whole ice core was cut into 5 cm sections and the outer parts of the samples were removed in a cold room under a laminar flow hood. For particle analyses, selected samples were melted and filtered under a laminar flow hood. The 10 - 20 ml of meltwater was filtered just after melting with Nuclepore polycarbonate membranes (25 mm diameter and 0.2 mm pore size) using a vacuum filter system. Each sample was filtered through separate filter membranes. Filter membranes were glued onto the stubs using carbon-coated double-sided tape and coated with a thin film of carbon. Samples were analysed for major elements using a Jeol JMS-6400 scanning electron microscope combined with a Link ISIS and INCA energy dispersive spectrometer. An acceleration voltage of 15 kV and a beam current of 1.2 nA were used for the SEM-EDS (scanning electron microscope energy dispersive spectrometer) analysis with the sample distance of 15 mm. Acidity was measured using a Radiometer Copenhagen PHM 205 pH meter and XC 161 combined pH electrode. For acidity measurements, samples were melted under nitrogen atmosphere to prevent carbon dioxide dissolution.

All the ions (Na^+, K^+, NH_4^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}, $CH_3SO_3^-$) were analysed over the whole core in 5 - 10 cm resolution using a Dionex ion chromatograph with conductivity detector and suppressor housed in a clean laboratory. Details for ion chromatography analyses are described by Kekonen et al. (2002) and Kekonen et al. (2004).

$\delta^{18}O$ was determined using a Finnigan-MAT Delta-E mass spectrometer (Isaksson et al. 2001). Results are measured against laboratory internal standard water, which has been calibrated on the V-SMOW/SLAP scale using the international reference materials V-SMOW (Vienna Standard Mean Oceanic Water) and SLAP (Standard Light Antarctic Precipitation) from the International Atomic Energy Agency. Reproducibility of replicate analyses is generally better than ±0.1 ‰.

We used an automated particle analyser to measure the chemical composition of all the particles present on a 271 × 191 mm subsections of the 490 mm^2 filter membrane. In total we analysed 2063 particles in 44 different subsections of the same filter membrane.

Results and discussion

There are no visible dust or tephra bands in the ice core, but particles were sought at many depths using the method described above. Enormous amounts of tephra (approximately half a million particles) were detected on the 66.99 - 67.04 m depth filter membrane. The subsection typically contained 30 - 100 particles, most commonly 50. (For comparison, at other depths a subsection usually contained less than 10 particles.) This is the only depth where tephra were found close to a high sulphate and acidity peak (66.69 - 66.89 m) (Fig. 2). Most of the tephra were small sand particles of basaltic composition (Fig. 3). The SiO_2 composition is approximately same as in particles originating from Laki eruption as reported in the literature (see references in Table 1). While the automated analyses in Fig. 3 do not give very exact chemical compositions due to the nature of the particle morphology, the large numbers of analyses give a statistical view of tephra composition relative to the composition of the Laki tephra.

A volcanic ash particle (that is, an amorphous glassy shard indicative of volcanic eruption activity) was found amongst the many sand particles (Fig. 4) and was analysed in detail using a spot analyser at 40 points on the particle. Comparison of the chemical composition of the particle with the composition of tephra from known eruptions indicates that particles found in the Lomonosovfonna ice core originate from the volcanic eruption of Laki in 1783 (Table 1). The tephra (including sand and ash) was ejected into the atmosphere by the fissure eruption mechanism that is typified by the Laki eruption (Fiacco et al. 1994). Atmospheric transport directed the Laki aerosol plume first to the east and the north-east (Thordarson & Self 2003) (Fig. 1). Since Svalbard is rather near to Iceland—less than 2000 km—and generally downwind of it, many heavy sand particles in addition to ash particles are observed in the core.

The volcanic tephra layer is about 10 - 20 cm deeper than the high sulphate concentration and acidity peaks (seen between 66.69 and 66.89 m)

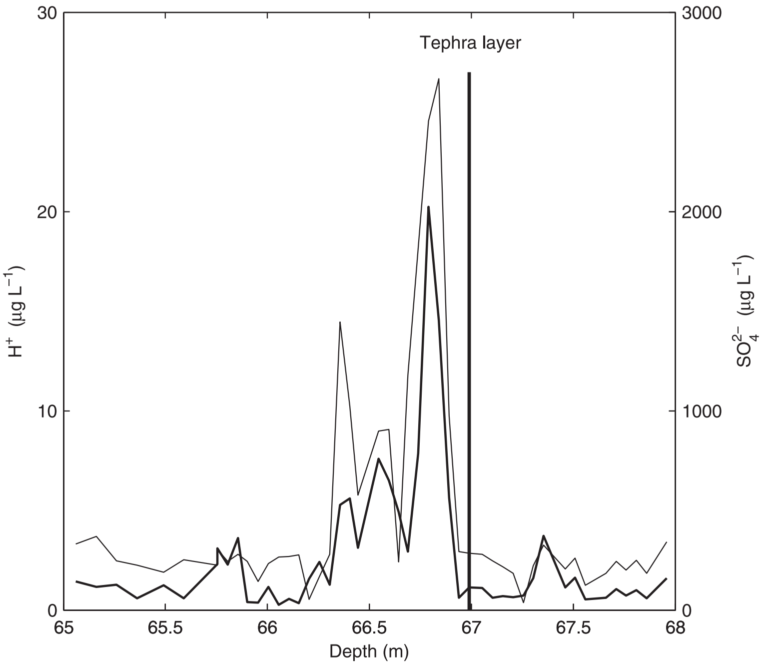

Fig. 2. Sulphate (thick line) concentrations and acidity (thin line) near the Laki peak. The tephra layer is marked by the thick black vertical line.

(Fig. 2). At this depth (66 - 67 m), the 5 cm sample resolution roughly corresponds to few months of time. This indicates that the volcanic tephra was carried to Lomonosovfonna ice cap about 3 - 9 months before the sulphuric acid started to precipitate on the glacier, and 6 - 12 months before the main sulphuric acid precipitation occurred. Sulphuric acid precipitation on the Lomonosvfonna ice cap lasted for 9 - 15 months. ECM analyses of Greenland ice cores (Clausen et al. 1997) indicate that the fallout from the Laki eruption lasted 1.0 and 1.6 years there.

After the main sulphate concentration and acidity peaks, a smaller peak can also be observed (Figs. 2, 5). Thordarson et al. (1996) reported that high discharge basaltic eruptions, such as

Table 1. Mean value and standard deviation for the 40 spot analysis of volcanic ash particle (Fig. 4) compared to other Laki particles. "Ref. 1" is the composition of the glass phase of the Laki eruption. An average of six samples and ten glass grains were analysed in each sample (. Grönvold, pers. comm. 2002). Refs. 2 and 3 are the composition of Laki tephra (T. Thordarson, unpubl. data; Fiacco et al. 1994). Ref. 4 is the composition of particles from filter paper collected from the GIPS2 ice core (Fiacco et al. 1994). Ref. 5 is the major element composition of Laki glass (Thordarson et al. 1996). The number of analyses is shown in the last column (n).

wt. %	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	MnO	FeO	n
Mean	2.81	6.59	13.16	50.64	0.45	0.18	10.20	2.07	0.03	13.85	40
SD	0.50	0.65	0.56	1.09	0.22	0.12	1.17	0.23	0.09	1.50	
Ref. 1	2.61	5.32	12.70	49.10		0.47	10.10	2.96	0.24	13.70	
Ref. 2	2.78	5.40	13.26	49.97		0.44	9.90	3.02	0.21	14.08	18
SD	0.11	0.02	0.02	0.07		0.01	0.03	0.01	0.00	0.05	
Ref. 3	1.83	5.48	12.96	54.47		0.50	9.23	2.84		12.69	3
SD	0.18	0.47	1.56	1.05		0.01	0.59	0.35		1.01	
Ref. 4	1.26	4.81	13.05	52.26		0.69	10.41	2.88		14.64	5
SD	0.52	0.65	0.95	2.45		0.25	0.90	0.34		2.59	
Ref. 5	2.84	5.78	13.05	49.68		0.42	10.45	2.96	0.22	13.78	21
SD	0.12	0.30	0.48	0.36		0.05	0.28	0.17	0.03	0.61	

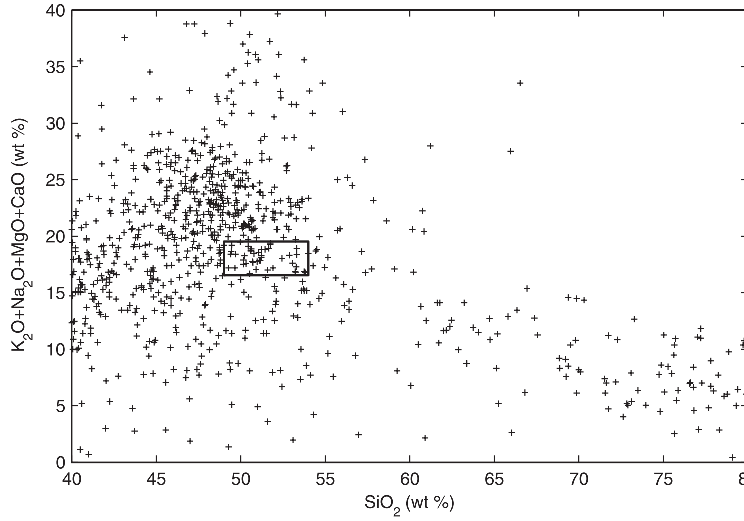

Fig. 3. Chemical compositions of 2063 particles by automated analysis in 44 different subsections of the membrane filter from a depth of 66.99 m. The box shows the chemical composition of Laki volcanic ash particles from the literature cited in Table 1.

Laki, are able to loft huge quantities of gas to altitudes (including the troposphere and lower stratosphere) where the resulting aerosol can reside for 1 - 2 years (Stevenson et al. 2003). In Greenland ice cores high sulphate peaks are observed in spring, summer and autumn 1784, indicating that the increased atmospheric loading of SO_2 lasted for about a year (Fiacco et al. 1994; Thordarson et al. 1996). The highest sulphate concentration observed in the Greenland ice cores is about 1300 µg L^{-1} (Fiacco et al. 1994), which is slightly lower than we observe in the Lomonosvfonna ice core (Fig. 2). The mean acidity of the Laki signal is 18 ± 8 µg L^{-1}. Thordarson & Self (2003) estimated the excess optical depth caused by the eruption relative to that due to the absolutely calibrated Krakatau aerosol cloud with a correction for the different geographic extent of the volcanic clouds. The method requires only the mean amplitude of the acidity of the Laki peak in Greenland ice cores, and produces an excess optical depth of 0.8 ± 0.4. Applying the same procedure to the Lomonosovfonna acidity record results in an excess optical depth of 0.9 ± 0.4, which is in excellent agreement with Thordarson & Self (2003). Clausen et al. (1997) report acidic fallout in central and southern Greenland ice cores (147 and 177 kg km^{-2}, respectively). This compares with a fallout preserved in the Lomonosovfonna ice core of 390 kg km^{-2}. This much larger fallout is a consequence of Svalbard being virtually downwind of Iceland during the eruption, while southern and, especially, central Greenland were essentially upwind.

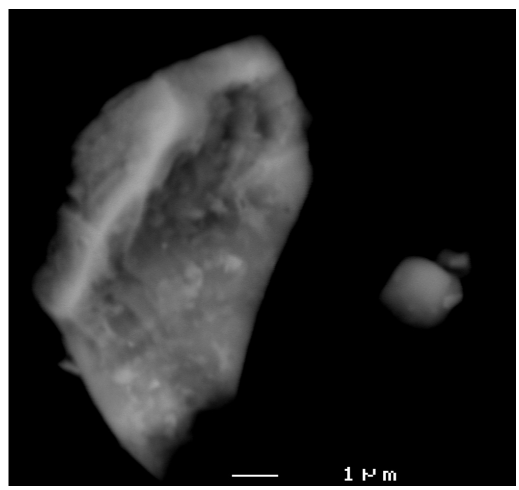

Fig. 4. A volcanic ash particle from a depth of 66.99 m.

The impact of the large acidity pulse on European temperatures has been well documented using various historical and proxy archives (Thordarson & Self 2003). The impact on the Lomonosovfonna $\delta^{18}O$ isotopic temperature proxy (Isaksson et al. 2003) can be seen in Fig. 5. It is clear that there is an immediate drop in $\delta^{18}O$ following the acid deposition rather than the ash fallout recorded by the tephra layer deposit. There is a 0.8 ‰ dip in 3-year running means relative to 30-year running means in $\delta^{18}O$ for the 3 years following the acidic fallout, and this represents the lowest value of $\delta^{18}O$ between 1400 and the

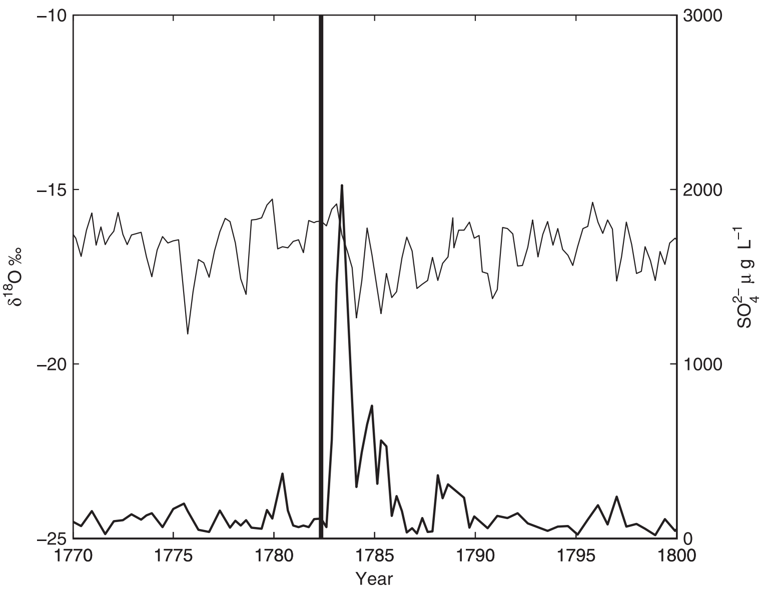

Fig. 5. Sulphate (thick line) concentrations and isotope $\delta^{18}O$ value (thin line) as a proxy for temperature near the Laki sulphate peak. The tephra layer is marked by the thick black vertical line.

1820s, and may therefore be regarded as highly significant. This is in contrast with the signal in the Greenland ice cores, where either a modest rise in $\delta^{18}O$ or no change is seen immediately following the eruption (Vinther et al. 2003). However, this apparent discrepancy may be explained by the larger acidic fallout to the west of Iceland over Europe and Svalbard, and the typical see-saw behaviour of the North Atlantic Oscillation, resulting in temperature anomalies of opposite sign over Europe and Greenland, (e.g. Vinther et al. 2003).

We can calibrate the $\delta^{18}O$–temperature relationship with borehole thermometry. Van de Wal et al. (2002) analysed the borehole temperature profile, finding that temperatures in the 19th century were 2.4 °C colder than the 20th century. This compares with a 0.8 ‰ difference in $\delta^{18}O$ (Isaksson et al. 2003) between the 19th and 20th centuries—virtually the same depression as caused by the Laki eruption. Thus we can estimate that the 3 year dip in $\delta^{18}O$ corresponds to about a 2.4 °C temperature fall. We could also use a calibration of isotopes against instrumental temperature records. However, extrapolating the calibrations to the colder pre-20th century period is unreliable (e.g. von Storch et al. 2004), so we prefer to use the estimate based on the borehole temperature profile. Highwood & Stevenson (2003) and Thordarson & Self (2003) observed in their calculations that temperature decreased 0.21 °C and 1.3 °C, respectively, in the wider Northern Hemisphere after the Laki eruption.

There are several reasons why the temperature drop in Svalbard may have been higher than in mainland Europe. It is clear that recovery to more normal temperatures takes at least two to three years (Thordarson & Self 2003). Although the Laki eruption probably did not eject aerosol into the upper stratosphere (Stevenson et al. 2003), where long residence times are possible, the long-lasting nature of the eruption helped to produce a persistent temperature depression, at least over much of Europe. The North Atlantic sea surface temperatures during the period 1780–1820 were monitored by the British Admiralty and are discussed by Bjerknes (1964): the ocean south of 40° N was up to 3 °C warmer than the present climate, while the northerly parts were 2 - 3 °C cooler. This condition would readily lead to increased sea ice cover in the Greenland, Iceland and Barents seas, providing a ready positive feedback mechanism for a year or two. Feedbacks with the large-scale atmospheric circulation patterns similar to those found for more recent eruptions (Kirchner et al. 1999) may also have enhanced the impact of the eruption.

Conclusions

The insoluble fractions of ice core samples show that during the 1783 Laki volcanic eruption massive amounts of tephra arrived to the Lomonosovfonna ice cap in Svalbard. The volcanic tephra layer includes large amounts of sand particles which suggests that not only light ash particles were well transported downwind from the eruption site. The heavy particles would also have been resistant to removal on the ice cap by wind. The tephra layer was found 10 - 20 cm deeper than high sulphate concentrations and acidity and shows that tephra arrived to the ice cap 6 - 12 months earlier than gaseous sulphur dioxide was rained out as sulphuric acid. The sulphuric acid precipitation lasted 9 - 15 months. Analyses indicate that the geochemical compositions of the volcanic tephra are basaltic, and the geochemical signatures of an ash particle show derivation from the Icelandic Laki volcanic eruption in 1783.

Acknowledgements.—The authors thank the Finnish Forest Research Institute Research Station in Rovaniemi for cold and clean room facilities and Aslak Grinsted for helpful analyses. The drilling of the Lomonosovfonna 1997 ice core was financed by the Norwegian Polar Institute and the Institute for Marine and Atmospheric Research, Utrecht. The laboratory work presented here was funded by the Finnish Academy Figare project. Elisabeth Isaksson, Veijo Pohjola, Roderik van de Wal and all the field participants are also thanked.

References

Bjerknes, J. 1964: Atlantic air–sea interaction. *Adv. Geophys. 10*, 1–82.

Clausen, H. B., Hammer, C. U., Hvidberg, C. S., Dahl-Jensen, D. & Steffensen, J. P. 1997: A comparison of the volcanic records over the past 4000 years from the Greenland Ice Core Project and Dye 3 Greenland ice cores. *J. Geophys. Res. 102(C12)*, 26707–26723.

Fiacco, R. J., Thordarson, T., Germani, M. S., Self, S., Palais, J. M., Whitlow, S. & Grootes, P. M. 1994: Atmospheric aerosol loading and transport due to the 1783–84 Laki eruption in Iceland, interpreted from ash particles and acidity in the GISP2 ice core. *Quat. Res. 42*, 231–240.

Grönvold, K., Óskarsson, N., Johnsen, S. J., Clausen, H. B., Hammer, C. U., Bond, G. & Bard, E. 1995: Ash layer from Iceland in the Greenland GRIP ice core correlatred with oceanic and land sediments. *Earth Planet. Sci. Lett. 135*, 149–155.

Highwood, E. J. & Stevenson, D. S. 2003: Atmospheric impact of the 1783–1784 Laki eruption. Part II: climatic effect of sulphate aerosol. *Atmos. Chem. Phys. 3*, 1177–1189.

Isaksson, E., Hermanson, M., Hicks, S., Igarashi, M., Kamiyama, K., Moore, J. C., Motoyama, H., Muir, D., Pohjola, V., Vaikmäe, R. & van de Wal, R. 2003: Ice core from Svalbard—useful archives of past climate and pollution history. *Phys. Chem. Earth 28*, 1217–1228.

Isaksson, E., Pohjola, V., Jauhiainen, T., Moore, J., Pinglot, J. F., Vaikmäe, R., van de Wal, R. S. W., Hagen, J. O., Ivask, J., Karlöf, L., Martma, T., Meijer, H. A. J., Mulvaney, R., Thomassen, M. & van den Broeke, M. 2001: A new ice core record from Lomonosovfonna, Svalbard: viewing the data between 1920–1997 in relation to present climate and environmental conditions. *J. Glaciol. 47*, 335–345.

Kekonen, T., Moore, J., Mulvaney, R., Isaksson, E., Pohjola, V. & van de Wal, R. S. W. 2002: An 800 year record of nitrate from the Lomonosovfonna ice core, Svalbard. *Ann. Glaciol. 35*, 261–265.

Kekonen, T., Moore, J., Perämäki, P., Mulvaney, R., Isaksson, E., Pohjola, V. & van de Wal, R. S. W. 2005: The 800 year long ion record from the Lomonosovfonna (Svalbard) ice core. *J. Geophy. Res. 110(D7)*, 10.1029/2004JD005223.

Kekonen, T., Perämäki, P. & Moore, J. C. 2004: Comparison of analytical results for chloride, sulfate and nitrate obtained from adjacent ice core samples by two ion chromatographic methods. *J. Environ. Monit. 6*, 147–152.

Kirchner, I., Stenchikov, G., Graf, H.-F., Robock, A. & Antuna, J. 1999: Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption. *J. Geophys. Res. 104(D16)*, 19039–19055.

Moore, J. C., A. Grinsted, T., Kekonen & Pohjola, V. 2005: Separation of melting and environmental signals in an ice core with seasonal melt. *Geophys. Res. Lett.* doi:10.1029/2005GL023039

Nye, J. F. 1963: Correction factor for accumulation measured by the ice thickness of the annual layers in an ice sheet. *J. Glaciol. 4*, 785–788.

Palais, J. M., Germani, M. S. & Zielinski, G. A. 1992: Interhemispheric transport of volcanic ash from a 1259 A.D. volcanic eruption to the Greenland and Antarctic ice sheets. *Geophys. Res. Lett. 19*, 801–804.

Pohjola, V. A., Martma, T., Meijer, H. A. J., Moore, J. C., Isaksson, E., Vaikmäe, R. & van de Wal, R. S. W. 2002: Reconstruction of 300 years annual accumulation rates based on the record of stable isotopes of water from Lomonosovfonna, Svalbard. *Ann. Glaciol. 35*, 57–62.

Stevenson, D. S., Johnson, C. E., Highwood, E. J., Gauci, V., Collins, W. J. & Derwent, R. G. 2003: Atmospheric impact of the 1783–1784 Laki eruption. Part I: chemistry modelling. *Atmos. Chem. Phys. 3*, 487–507.

Thordarson, T. & Hoskuldsson, A. 2002: *Classic geology in Europe. 3: Iceland.* Herts, UK: Terra Publishing.

Thordarson, T., Miller, D. J., Larsen, G., Self, S. & Sigurdsson H. 2001: New estimates of sulphur degassing and atmospheric mass-loading by the 934 AD Eldgjá eruption, Iceland. *J. Volcan. Geotherm. Res. 108*, 33–54.

Thordarson, T. & Self, S. 2003: Atmospheric and environmental effects of the 1783–1784 Laki eruption: a review and reassessment. *J. Geophys. Res. 108(D1)*, 4011–4039.

Thordarson, T., Self, S., Óskarsson, N. & Hulsebosch, T. 1996: Sulfur, chlorine, and fluorine degassing and atmospheric loadings by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland. *Bull. Volcan. 58*, 205–225.

van de Wal, R. S. W., Mulvaney, R., Isaksson, E., Moore, J. C., Pinglot, J.-F., Pohjola, V. & Thomassen, M. P. A. 2002: Reconstruction of the historical temperature trend from measurements in a medium-length bore hole on the Lono-

mosovfonna Plateau, Svalbard. *Ann. Glaciol. 35*, 371–378.
Vinther, B. M., Johnsen, S. J., Andersen, K. K., Clausen, H. B. & Hansen, A. W. 2003: NAO signal recorded in the stable isotopes of Greenland ice cores. *Geophys. Res. Lett. 30*, doi:10.1029/2002GL016193.
von Storch, H., Zorita, E., Jones, J. M., Dimitriev, Y., González-Rouco, F. & Tett, S. F. B. 2004: Reconstructing past climate from noisy data. *Science 306(5696)*, 10.1126/science.1096109.
Watanabe, O., Motoyama, H., Igarashi, M., Kamiyama, K., Matoba, S., Goto-Azuma, K., Narita, H. & Kameda, T. 2001: Studies on climatic and environmental changes during the last hundred years using ice cores from various sites in Nordaustlandet, Svalbard. *Mem. Natl. Inst. Polar Res. Spec. Iss. 54*, 227–242.
Zielinski, G. A., Fiacco, R. J., Mayewski, P. A., Meeker, L. D., Whitlow, S., Twickler, M. S., Germani, M. S., Endo, K. & Yasui, M. 1994: Climatic impact of the A.D. 1783 Asama (Japan) eruption was minimal: evidence from the GISP2 ice core. *Geophys. Res. Lett. 21*, 2365–2368.
Zielinski, G. A. & Germani, M. S. 1998: New ice-core evidence challenges the 1620s BC age for the Santorini (Minoan) Eruption. *J. Archaeol. Sci. 25*, 279–289.
Zielinski, G. A., Mayewski, P. A., Meeker, L. D., Grönvold, K., Germani, M. S., Whitlow, S., Twickler, M. S. & Taylor, K. 1997: Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores. *J. Geophys. Res. 102(C12)*, 26 625–26 640.