University of New Hampshire
University of New Hampshire Scholars' Repository

Faculty Publications

Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores

Gregory A. Zielinski
University of New Hampshire, Durham

Paul A. Mayewski
University of Maine

L. David Meeker
University of New Hampshire, Durham

Karl Gronvold

Mark S. Germani

See next page for additional authors

Follow this and additional works at: https://scholars.unh.edu/faculty_pubs

Recommended Citation

Zielinski, G. A., Mayewski, P. A., Meeker, L. D., Grönvold, K., Germani, M. S., Whitlow, S., . . . Taylor, K. (1997). Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores. Journal of Geophysical Research: Oceans, 102(C12), 26625-26640. doi:10.1029/96JC03547

Authors

Gregory A. Zielinski, Paul A. Mayewski, L. David Meeker, Karl Gronvold, Mark S. Germani, Sallie I. Whitlow, Mark S. Twickler, and Kendrick C. Taylor

Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores

Gregory A. Zielinski,[1] Paul A. Mayewski,[1] L. David Meeker,[1] Karl Grönvold,[2] Mark S. Germani,[3] Sallie Whitlow,[1] Mark S. Twickler,[1] and Kendrick Taylor[4]

Abstract. The recently collected Greenland Ice Sheet Project 2 (GISP2) and Greenland Ice Core Project ice cores from Summit, Greenland, provide lengthy and highly resolved records of the deposition of both the aerosol (H_2SO_4) and silicate (tephra) components of past volcanism. Both types of data are very beneficial in developing the hemispheric to global chronology of explosive volcanism and evaluating the entire volcanism-climate system. The continuous time series of volcanic SO_4^{2-} for the last 110,000 years show a strong relationship between periods of increased volcanism and periods of climatic change. The greatest number of volcanic SO_4^{2-} signals, many of very high magnitude, occur during and after the final stages of deglaciation (6000-17,000 years ago), possibly reflecting the increased crustal stresses that occur with changing volumes of continental ice sheets and with the subsequent changes in the volume of water in ocean basins (sea level change). The increase in the number of volcanic SO_4^{2-} signals at 27,000-36,000 and 79,000-85,000 years ago may be related to initial ice sheet growth prior to the glacial maximum and prior to the beginning of the last period of glaciation, respectively. A comparison of the electrical conductivity of the GISP2 core with that of the volcanic SO_4^{2-} record for the Holocene indicates that only about half of the larger volcanic signals are coincident in the two records. Other volcanic acids besides H_2SO_4 and other SO_4^{2-} sources can complicate the comparisons, although the threshold level picked to make such comparisons is especially critical. Tephra has been found in both cores with a composition similar to that originating from the Vatnaöldur eruption that produced the Settlement Layer in Iceland (mid-A.D. 870s), from the Icelandic eruption that produced the Saksunarvatn ash (~10,300 years ago), and from the Icelandic eruption(s) that produced the Z2 ash zone in North Atlantic marine cores (~52,700 years ago). The presence of these layers provides absolute time lines for correlation between the two cores and for correlation with proxy records from marine sediment cores and terrestrial deposits containing these same tephras. The presence of both rhyolitic and basaltic shards in the Z2 ash in the GISP2 core and the composition of the basaltic grains lend support to multiple Icelandic sources (Torfajökull area and Katla) for the Z2 layer. Deposition of the Z2 layer occurs at the beginning of a stadial event, further reflecting the possibility of a volcanic triggering by the effects of changing climatic conditions.

1. Introduction

Since the pioneering work of *Hammer et al.* [1980], the records of past volcanic activity available in ice cores continue to expand on the global chronology of

explosive volcanism and to increase our understanding of the atmospheric and climatic impact of past eruptions. The advantage of using ice cores in this line of research over other records is the ability to develop continuous time series that at least can extend through the last glacial/interglacial cycle at a resolution that can be subannual to several decades per sample. Although marine records are continuous and lengthy, their best resolution is of the order of decades, the coarsest resolution often available in ice cores. Terrestrial records are not continuous except in the cases of lake sediment and possibly bog records. Volcanic records developed from these sources inevitably are much shorter than ice-core records. Most importantly, ice cores provide the opportunity to directly detect and measure both the widely distributed (hemispherically to globally) climate-forcing

[1] Climate Change Research Center, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham.
[2] Nordic Volcanological Institute, University of Iceland, Reykjavik.
[3] MVA, Inc., Burr Ridge, Illinois.
[4] Desert Research Institute, University of Nevada, Reno.

aerosol component (H_2SO_4) and the silicate component (tephra). This contrasts with other sources (e.g., tree rings) that record a climatic effect of the eruption, not the eruptive products themselves. Further, it is only the silicate component that is available in marine and terrestrial records.

Two different parameters measured in ice cores are used successfully to develop records of past volcanism through the time series of volcanic aerosol deposition. The earliest volcanic records in ice cores were based on the electrical conductivity method (ECM), as correlated with pH measurements, and thus a direct measurement of the acidity of the ice [e.g., *Hammer*, 1980; *Hammer et al.*, 1980; *Clausen and Hammer*, 1988]. Higher conductivity values reflect greater acid deposition. In the case of the deposition of volcanic aerosols, this is commonly the H_2SO_4 component, although other volcanic acids (HCl and HF) may be contained in the ECM signal [e.g., *Taylor et al.*, 1992]. More recently, complete suites of major ion concentrations have been measured in ice cores, including SO_4^{2-}, thereby yielding a direct measurement of the H_2SO_4 component [e.g., *Legrand and Delmas*, 1987; *Mayewski et al.*, 1993]. Other sources of SO_4^{2-} (sea salt, continental salts, biogenic SO_4^{2-}) complicate interpretation of this signal. Despite these and other potential problems in developing a volcanic signal from ice cores [*Robock and Free*, 1995], these are still the most lengthy and continuous records of a direct eruptive product presently available. Moreover, regardless of whether the ECM or major ion records are used, the results can ultimately lead to an estimate of the amount of atmospheric loading resulting from a particular eruption and its climatic impact [e.g., *Clausen and Hammer*, 1988; *Delmas et al.*, 1992; *Zielinski*, 1995].

The location and identification of tephra in ice cores raise the significance of the volcanic records available in this medium to much greater levels. Determining the source volcano of the tephra, through a match of the chemistry of the volcanic glass found in the ice core with that from the particular eruption [e.g., *Palais et al.*, 1991; *Grönvold et al.*, 1995], can verify the eruption responsible for the volcanic aerosol signal observed. The presence of two distinct glass populations can indicate the presence of aerosols from multiple eruptions or provide evidence of the eruptive processes for a known eruption [*Zielinski et al.*, 1995]. The ability to reliably identify the eruption(s) responsible for a particular signal provides the information needed to clearly assess the climatic-forcing capability of a particular eruption/volcano and the particular type of eruption (e.g., a plinian versus fissure type of eruption). Further, the presence of tephra from a known eruption provides an absolute time line for developing the depth/age scale of the ice core. Even if the source eruption is not known, volcanic glass in an ice core can allow for correlation among ice cores and, importantly, the direct correlation of the ice-core paleoclimatic records with those available in deep-sea sediment cores [*Grönvold et al.*, 1995] and terrestrial records (especially continuous lake and bog records) containing the same tephra.

This paper presents results from paleovolcanic studies on the two deep ice cores recently collected from the summit of the Greenland Ice Sheet, Greenland Ice Sheet Project 2 (GISP2) and Greenland Ice Core Project (GRIP). Initially, we will summarize the time series of volcanic aerosol deposition in the GISP2 core available in both the continuous glaciochemical (i.e, SO_4^{2-}) and ECM records. We will present the 110,000-year record of volcanism derived from the SO_4^{2-} time series and the Holocene record of volcanism derived from the ECM record. This discussion will help place the volcanic record in perspective to climatic change over the last 110,000 years and to other parameters measured in both ice cores and presented in this special issue. Complete details of the entire GISP2 volcanic SO_4^{2-} record are presented elsewhere [*Zielinski et al.*, 1996a]. The continuous volcanic record in the GRIP core for the last 4000 years, as developed by ECM, is presented in this volume [see *Clausen et al.*, this issue].

The second part of the paper will present the results of the detailed study of three tephra layers found in each of the two cores. This does not mean that these are the only three layers found in each core but that these are the only three that have been sampled to date. The three layers are believed to be equivalent to the Settlement Layer in Iceland, the Saksunarvatn ash, and the deep marine Z2 ash layer. The Saksunarvatn and Z2 equivalents are visible to the naked eye, whereas the Settlement Layer was not. All three tephra have an Icelandic source, but we have found tephra from other volcanic regions of the northern hemisphere [e.g., *Palais et al.*, 1992]. We also will discuss the implications of finding these three layers both in relation to eruptive processes and in terms of their importance as a stratigraphic marker for correlation among records in the North Atlantic region.

2. Methodology

The glaciochemical record of the GISP2 core was developed by continuous sampling over the entire length to develop a time series of major ions including SO_4^{2-} [*Mayewski et al.*, this issue]. Concentrations of individual ions were determined with an ion chromatograph [*Buck et al.*, 1992]. The deposition of volcanically derived SO_4^{2-} is noted by the presence of large SO_4^{2-} spikes much above background levels. The coincidence of these spikes with the timing of known explosive volcanic eruptions supports this concept. We previously presented the first 9000 years of the volcanic record in the GISP2 core by using the residuals over a robust spline smoothing of the raw SO_4^{2-} data and a discriminant analysis of the complete chemistry suite [*Zielinski et al.*, 1994]. At 9000 years ago, baseline levels for SO_4^{2-} changed. During the glacial the added input from continental salts (e.g., $CaSO_4$) makes a direct detection of volcanic SO_4^{2-} by the presence of large SO_4^{2-} spikes much harder. To alleviate this problem, we used an empirical orthogonal function (EOF, i.e., a

type of discriminant analysis [*Mayewski et al.*, 1994]) to identify peaks due to the deposition of volcanic aerosols. A good correlation between the volcanic record developed by the EOF analysis and that produced in our initial work for the last 9000 years supported the EOF time series for the 110,000-year record. Specific details on how the EOF was used in developing the volcanic record are presented by *Zielinski et al.* [1996a].

Sampling for the glaciochemical record was at a biyearly resolution through the Holocene ($\sim$11,700 years ago). Sampling resolution then decreased to 3-5 years $\sim$11,700-14,800 years ago, 8-10 years $\sim$14,800-18,200 years ago, and between 10 and 15 years from 18,200 to about 51,000 years ago, with a gradual decrease to about 50 yr/sample around 90,000 years ago. This decrease in temporal resolution with time results in a decrease in the number and magnitude of volcanic signals with time. By sampling a section of core at both a biyearly sampling resolution and at the coarser sampling resolution (in this case about 12 yr/sample) [*Zielinski et al.*, 1996a], we were able to determine that the change in sampling reduced the number of events with a volcanic SO_4^{2-} concentration $\geq$75 ppb by 3 times for every 5 times decrease in sampling resolution relative to the Holocene. A SO_4^{2-} concentration $\geq$75 ppb is similar to that associated with historical equatorial and midlatitude northern hemisphere eruptions known to have perturbed climate [e.g., *Self et al.*, 1981]. Using that ratio we projected the number of eruptions per millennium that we may have missed in our record for the past 110,000 years [*Zielinski et al.*, 1996a]. That is also presented here for comparison. Details on the development of the depth/age scale for the GISP2 core are presented by *Meese et al.* [1994] and are discussed elsewhere in this volume. Error estimates for ages within the GISP2 core are generally more conservative than those for the GRIP core.

The electrical conductivity method [*Hammer*, 1980; *Hammer et al.*, 1980; *Taylor et al.*, 1992] was used to determine the acidity of the ice. The direct current flowing between two electrodes with a potential difference of 2100 V was measured every millimeter along the core. Unlike an aqueous solution where all the ions in solution are sufficiently mobile to conduct an electrical charge, in ice the majority of ions are bound in the ice lattice and do not contribute significantly to the conduction of a direct current. The flow of direct current in ice has been shown to be nonlinearly related to the concentration of mobile protons (H^+) associated with strong acids [*Hammer et al.*, 1980; *Moore et al.*, 1992]. Volcanic eruptions and other sources of acids will increase the concentration of mobile protons and increase the ECM. Similarly, a decrease in neutralizing material will also increase the concentration of mobile protons and increase the ECM. A strength of the ECM is that it is able to resolve acidic features in the core that are less than a centimeter thick. In the Holocene portion of the core this yields 20 to 200 samples/yr, allowing short-duration features to be well resolved. This can be important for resolving smaller volcanic events

that influence the sulfate record for less than a year. Eruptions which influence the chemistry for more than 2 years should be well recorded on the sulfate record. Corrections have been made to minimize the influence of unavoidable differences in ice temperature that obtained while the ECM measurement was being made. The presence of large amounts of alkaline dust in the stadial portions of Greenland ice cores neutralizes the acids in the cores and reduces the ECM by about 2 orders of magnitude. Because exceptionally high levels of acids are required to overcome the high levels of neutralizing alkaline dust which occur during stadial periods, only the Holocene portion of the ECM record is considered in this paper.

The original ECM record is recorded as microamps of current flowing between the two electrodes. The ECM record has been processed to enhance the volcanic signatures in the record. A 10-year running average was calculated to determine the time-varying background level of the ECM. The difference between the ECM record and the background record was calculated, and the standard deviation of this difference was determined. The ECM results reported here are the number of standard deviation units that the ECM record is greater than the background ECM record.

We identified sections of the ice core that may contain volcanic glass by first pinpointing sections that contain volcanically derived aerosols as are available via the chemical or ECM records. Tephra grains can help scavenge acidic aerosols [*Rose*, 1977], although they apparently will rarely act as nuclei for H_2SO_4 aerosol formation in the stratosphere [*Sheridan et al.*, 1992]. Visible bands of debris were obvious in the lower parts of the core, although almost all of the visible sections analyzed in this study had high SO_4^{2-} or ECM spikes associated with them. Meltwater samples from all of these sections were first filtered or evaporated onto a cellulose membrane for examination with a scanning electron microscope (SEM). Upon locating volcanic glass, we then analyzed individual particles to determine major oxide compositions using a JEOL JXA-8600 automated microprobe in the case of the GISP2 core [*Palais et al.*, 1992; *Fiacco et al.*, 1993] and a Cambridge Stereoscan in the case of the GRIP core.

3. Volcanic Aerosols

We present two time series of volcanic aerosols from the GISP2 core to assess the relationship between climate change and volcanism. This relationship can take on two scenarios: one being the nature of the forcing of volcanism on climate as is often addressed [e.g., *Self et al.*, 1981; *Rampino et al.*, 1988] and a second relationship being the potential for the results of a shift in climate (i.e., crustal isostatic adjustment with deglaciation) forcing volcanism [e.g., *Grove*, 1976; *Rampino et al.*, 1979]. The amount of sulfur emitted from a volcanic eruption, which eventually forms H_2SO_4 aerosols in the stratosphere, is the essential component that determines whether a particular eruption can impact cli-
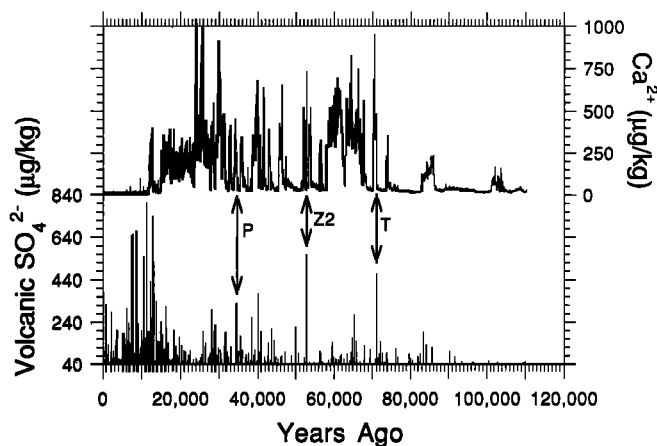
Figure 1. Relationship between volcanic SO_4^{2-}, as represented by EOF-5 (see text and Zielinski et al. [1996a] for discussion), and Ca^{2+} time series for the last 110,000 years. Age is years before A.D. 2000. Probable signals for some of the major volcanic eruptions discussed in text are shown: P, Phlegraean Fields eruption/Campanian Ignimbrite; Z2, Z2 ash layer; T, Toba.

mate. First, we summarize the 110,000-year record of volcanic SO_4^{2-} followed by a discussion on the implications of this record for the volcanism-climate system. Next, we present the Holocene ECM record as compared to that of the GISP2 volcanic SO_4^{2-} record and the implications of this comparison in paleovolcanic research. However, because this is a single ice core, individuals must be aware of the possible limitations in the data set [see Robock and Free, 1995; Zielinski, 1995], although comparisons of the ECM record may be made directly with the GRIP core over the last 4000 years [Clausen et al., this issue].

3.1. GISP2 Volcanic SO_4^{2-} Record: 110,000 Years

The complete 110,000-year volcanic SO_4^{2-} and Ca^{2+} records are presented on Figure 1. The Ca^{2+} record reflects continental dust deposition and is a proxy for climatic conditions, with high concentrations occurring during colder periods and low concentrations occurring during warmer periods [Mayewski et al., 1994, this issue]. There are several interesting aspects of the volcanic SO_4^{2-} record that we highlight here given the relationship between these two time series. More detailed discussion on the 110,000-year record is given by Zielinski et al. [1996a], although we add discussion here on the significance between our record and changes in glacioeustatic sea level.

Foremost is the large number of signals that occur between 6000 and 17,000 years ago and especially between 7000 and 13,000 years ago (Figure 1). Even after compensating for the decrease in temporal resolution of sampling, this period, which spans the final stages of deglaciation and the early Holocene, consistently contains the greatest number of signals per millennium (as well as some of the largest signals) in the entire record (Figure 2a). The second period of extensive volcan-
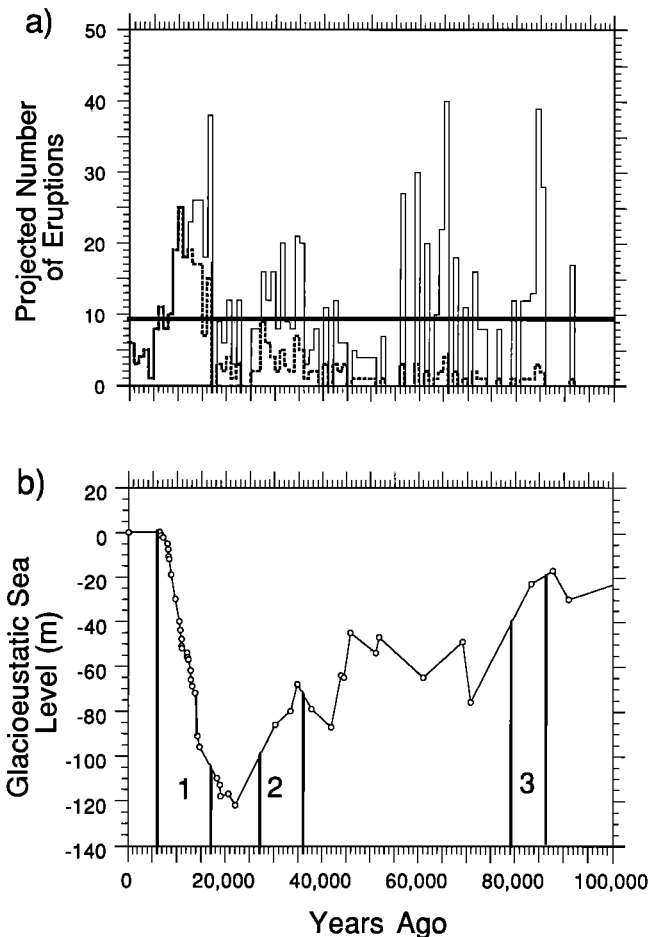

Figure 2. (a) Number of eruptions per millennium exceeding a volcanic SO_4^{2-} concentration of 74 ppb as recorded in the GISP2 core (dashed line). Because of the decrease in temporal resolution with depth, the SO_4^{2-} record given in Figure 1 does not record all eruptions, thus the continual decrease in eruptions per millennium with time (dashed line). However, we used the technique of Zielinski et al. [1996a] to produce a record of the projected number of eruptions (solid line) that may have occurred given a similar sampling resolution as to that for the Holocene. These two lines coincide for the first 12,000 years. (b) Relationship between periods of enhanced volcanic signals in the GISP2 core (periods 1-3) and glacioeustatic sea level change after Mayewski et al. [this issue].

ism occurs from around 27,000 to about 36,000 years ago (Figure 1). Although this is a longer period of increased volcanism than occurs during deglaciation, the number of events per millennium is generally lower than that during and immediately after deglaciation once the adjustment is made for sampling resolution (Figure 2a). The period 27,000-36,000 years ago is characterized by increasing Ca^{2+} concentrations leading to the last glacial maximum (Figure 1). The third most continuous period of enhanced volcanism occurs from 79,000 to 85,000 years ago (Figure 2a), which coincides with the initial stadial periods prior to the beginning of the last glaciation (Figure 1). It is projected that several millennium in the early stages of glaciation (about

70,000-78,000 years ago) may have had a greater number of eruptions than the period 6000-17,000 years ago, but these periods of elevated volcanism do not remain at such levels for more than 1 or 2 millennium, unlike during deglaciation.

The last aspect of the 110,000-year SO_4^{2-} record that we discuss is the relationship between the periods of high volcanic activity and sea level change. Others have proposed that there is a positive relationship between changing sea level and increased volcanism [e.g., *Matthews*, 1969; *McGuire et al.*, 1995]. Consequently, we placed the timing of the three most continuous periods of enhanced volcanism on a plot of glacioeustatic sea level taken from *Mayewski et al.* [this issue] (Figure 2b). The increased volcanism from 6000 to 17,000 years ago (period 1 on Figure 2b) coincides very well with the period having the greatest rate of sea level rise following deglaciation. Furthermore, the other two periods of enhanced volcanism (periods 2 and 3 on Figure 2b) occur at the beginning of the two periods whereby sea level was starting to fall with ice sheet growth prior to a major glacial period (i.e., corresponding to the Stage 2-3 and Stage 4-5 transitions of the marine isotope record, respectively).

We feel that our results very much support the suggestions presented by others that there is a link between increased volcanic activity and the increased crustal stresses that occur with changing volumes of continental ice sheets [e.g., *Rampino et al.*, 1979; *Kyle et al.*, 1981; *Sigvaldason et al.*, 1992] and with the subsequent changes in the volume of water in ocean basins (i.e., sea level change [*Matthews*, 1969; *Nakada and Yokose*, 1992; *Paterne and Guichard*, 1993; *Rampino and Self*, 1993; *McGuire et al.*, 1995]). For instance, if we first discuss the period of enhanced volcanism with deglaciation (period 1, Figure 2b), we note that the increased stresses with crustal unloading would probably have the greatest impact on the extensive volcanic zones of the northern hemisphere like Iceland and the North Pacific Rim. In fact, the large magnitude of many of these signals in the GISP2 core could reflect the quick transport of aerosols from proximal eruptions in Iceland and/or from Alaskan and Kamchatka/Kurile Islands eruptions immediately upwind of Greenland. Perhaps more significantly, our results appear to strongly support the idea that rate of sea level change and the associated stresses exerted on coastal and island volcanic systems may play the greatest role in inducing explosive volcanic activity [e.g., *Nakada and Yokose*, 1992; *Paterne and Guichard*, 1993; *McGuire et al.*, 1995]. *McGuire et al.* [1995] noted that the Mediterranean volcanic region was especially active during the period of rapid sea level rise between 8000 and 13,000 years ago, almost exactly congruent with the period of most frequent and greatest magnitude signals in the GISP2 core. *Paterne and Guichard* [1993] also noted that the periodicity of volcanic eruptions in the Campanian area of Italy corresponds well with orbital cycles and the subsequent changes in glacioeustatic pressures. We previously noted the probable deposition of aerosols on

Greenland from Mediterranean volcanoes like Vesuvius [*Zielinski et al.*, 1994; *Zielinski*, 1995] and the Campanian area (Phlegraean Fields (see *Zielinski et al.* [1996a] and below)).

The possible cause for the other two periods of continuously high volcanic activity (periods 2 and 3, Figure 2b) also may be related to the interaction between volcanism and the effects of climatic change. The buildup of ice in the northern hemisphere leading to the glacial maximum about 23,000 years ago (as reflected in the maxima in Ca^{2+} concentrations; Figure 1) may lead to the same increase in crustal stresses as occurs with a melting ice sheet. *Kyle et al.* [1981] previously suggested that increased volcanism in Antarctica may have been caused by an increase in the lithostatic pressure on upper crustal magma chambers with ice sheet thickening. Our data support the possibility of a similar scenario for northern hemisphere ice sheets. Because the maximum impact of volcanism on climate may only be of the order of decades [*Rind and Overpeck*, 1993], we do not think the increase in volcanism is forcing the climate change leading to ice sheet growth. However, it may enhance the growth to some extent (see relevant discussion by *Rampino and Self* [1993]). The short period of apparently enhanced volcanic activity 79,000-85,000 years ago also may be related to initial ice growth following the last interglacial.

Of additional interest is the period between 56,000 and 73,000 years ago. This period is marked by several millennia during which the projected number of eruptions is very high, although the periods of high volcanic activity are discontinuous compared to the other three periods discussed (Figure 2). Perhaps the lack of large swings in sea level change during this roughly 17,000-year period, given the existing glacioeustatic record (Figure 2b), may have inhibited the development of an extensive, continuous period of increased volcanism as occurred during deglaciation. Nevertheless, this time period of increased volcanic activity closely coincides with the ~10,000-year glacial period from about 57,000 to 68,000 years ago as recorded in the Ca^{2+} record (Figure 1). The 3000-year period from about 63,000 to 66,000 years ago (at the beginning of this glacial period) contains the highest number of projected eruptions. These results further substantiate the suggestion that ice sheet growth plays a role in forcing explosive volcanism.

An aspect of the record that is not so clear is why a large volcanic signal or group of signals occurs during some of the interstadial/stadial transitions but not during others (Figures 1 and 2). Three large volcanic signals that may be related to known eruptions (Figure 1) fall into this category [*Zielinski et al.*, 1996a]. These include the large Phlegraean Fields eruption in Italy that formed the Campanian Ignimbrite (ice-core signal 34,564 ± 4000 years ago, eruption 34,000 ± 3000 years ago [*Castagnoli et al.*, 1995]), the Icelandic eruptions that produced the Z2 ash zone in North Atlantic deep sea cores (as discussed below), and the Toba mega-eruption (ice-core signal 71,100 ± 5000 years ago
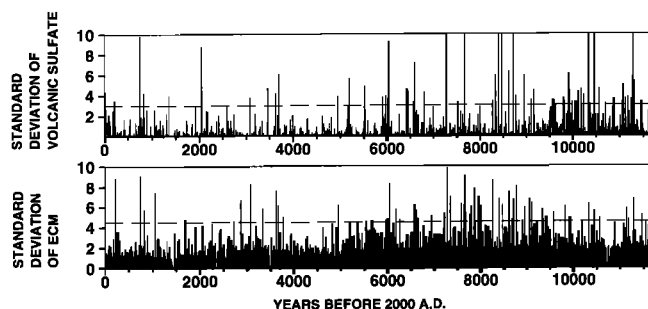
Figure 3. Holocene time series of ECM and volcanic SO_4^{2-} records in the GISP2 core showing numerous short-duration increases that are associated with volcanic activity. To facilitate comparison, volcanic SO_4^{2-} and ECM records are displayed in standard deviation units. The dashed lines indicate thresholds that were selected to make the comparisons discussed in the text.

[*Zielinski et al.*, 1996b], eruption 73,000 ± 4000 years ago [*Chesner et al.*, 1991]). The presence of increased volcanism during these transitions could be additional evidence of the relationship between volcanism and climate, but it is not a consistent relationship. One could infer that during some of these very rapid transitions (i.e., of the order of decades), ice growth/decay is not severe enough to enhance crustal stresses on magma chambers, thereby increasing volcanic activity. However, this is only speculation. Nevertheless, our results appear to support the presence of a strong feedback mechanism in the volcanism-climate system and a strong linkage among the lithosphere, hydrosphere (both the cryosphere and oceans), and atmosphere.

3.2. GISP2 ECM Record: Holocene

The Holocene ECM from the GISP2 core shows numerous increases in acidity with durations of less than a few years (Figure 3). These short-duration events are commonly considered to be of volcanic origin [*Hammer et al.*, 1980; *Wolff et al.*, 1995]. For the purpose of comparing the ECM and volcanic SO_4^{2-} records of the Holocene, arbitrary thresholds were used to identify volcanic events. For the volcanic SO_4^{2-} record a value of 3 standard deviation units was selected, and for the less chemically specific ECM a value of 4.5 standard deviation units was selected. These thresholds are sufficiently high that only the largest of volcanic events exceed the thresholds. During the Holocene portion of the record these thresholds were exceeded by presumably volcanic events 60 and 56 times on the ECM and volcanic SO_4^{2-} records, respectively. The thresholds were intentionally selected such that the number of events exceeding the thresholds during the Holocene would be nearly equal on the ECM and volcanic SO_4^{2-} records. For both the ECM and SO_4^{2-} records, slightly more than half (53% and 57%, respectively) of the events that exceed these thresholds occurred on the other record. This result is insensitive to the values that are used as long as the thresholds are selected such that they are exceeded an equal number of times by the ECM and volcanic SO_4^{2-} record.

The fact that there is some discrepancy between the ECM and volcanic SO_4^{2-} records is not surprising because of occasional poor core quality, analytical errors, the different temporal resolution of the methods, and the use of a simple two-class threshold classification. Moreover, most of the discrepancies between the records occur when one of the records is close to the threshold, suggesting that much of this discrepancy is a result of using a two-class threshold classification. In spite of this the observed discrepancies are still greater than anticipated. This suggests there may be an additional cause for a portion of the observed discrepancy between the identification of volcanic events by the ECM and SO_4^{2-}. The events which exceed the threshold on the ECM and do not exceed the threshold on the SO_4^{2-} record indicate either a source of acids that are not associated with SO_4^{2-} (such as volcanic HCl) or an episodic decrease in neutralizing compounds in the core (possibly due to a short-duration decrease in wind-transported alkaline dust). The events which exceed the threshold on the volcanic SO_4^{2-} record and do not exceed the threshold on the ECM indicate either an unknown nonacidic source of SO_4^{2-} or an abundance of neutralizing compounds deposited with SO_4^{2-} from an acidic source. With the limited present understanding of the nonlinear response of the ECM it would be speculative to use the available data to discriminate between these possible interpretations, but the SO_4^{2-} record is more uniquely associated than the ECM with the sulfuric volcanic events of extended duration. Although ice cores are among the best recorders of paleovolcanic events, there is still much to be learned regarding how to extract detailed information on single volcanic events from an ice core.

4. Tephrochronology

The three tephra sections found in both the GISP2 and GRIP cores provide absolute tie points between them at approximately 1100, 10,300, and 52,000 years ago. We have already found more recent absolute time lines in the GISP2 core via the identification of tephra from two historical Icelandic eruptions (i.e., A.D. 1783 Laki [*Fiacco et al.*, 1994]; A.D. 1362 Oræfajökull [*Palais et al.*, 1991]) and an absolute correlation point through the presence of tephra from the Icelandic Eldgjá eruption (mid-A.D. 930s [*Zielinski et al.*, 1995]). Continued analyses on each core in the near future should lead to the identification of other correlative tephra layers. For instance, several other layers containing tephra, thought to be from the Katla system in Iceland, have been found in the GRIP core [*Grönvold et al.*, 1995], thus providing guidance for future sampling in the GISP2 core. The fact that the same ash layers found in both ice cores are found either in the terrestrial record or in the marine record or in both types of media throughout parts of the North Atlantic region means that we can now provide absolute stratigraphic markers for many proxy data sets at least into the middle of the last glacial cycle. For each tephra layer, we first present and discuss

the aerosol record followed by a discussion of the tephra component. The results presented here expand on the work of *Grönvold et al.* [1995], who correlated some of the tephra in the GRIP core with known ash layers in the North Atlantic region. Note that we present the tephra compositions both in tabular form and on ternary diagrams. It is important to realize that the analysis of individual grains from ice cores (using energy dispersive spectrometry (EDS)) and the normalization to 100% can lead to more variability in the results compared to polished sections from terrestrial deposits (using wavelength dispersive spectrometry (WDS)). Thus, the average compositions of volcanic glass found in the tephra layers (Table 2) may not appear to overlap as well as the distribution of individual grains plotted on ternary diagrams. Different instrumentation also can lead to increased scatter in the data obtained from individual grain analysis on ice-core tephra.

4.1. Settlement Layer (~1100 Years Old)

The Settlement Layer is often used as a stratigraphic marker and refers to a distinct ash layer in Iceland that was deposited close to the time of the permanent Norse settlement of the country. The source of the deposit is the Vatnaöldur fissure in southern Iceland with part of the fissure system located within the Torfajökull central volcano [*Larsen*, 1984]. The eruption was very explosive, simultaneously producing both basaltic (1.1 km³ dense rock equivalent (DRE) from the SW end of the fissure system) and rhyolitic (0.1 km³ DRE from the NW end of the fissure system) tephra. Interestingly, distribution of the basaltic tephra is generally symmetrical around the major eruptive cones within the main fissure system and with a slight NW orientation to the main axis of deposition, but the silicic tephra is concentrated on the west side of its source cones in the southwest end of the fissure with a slightly greater NW elongation to the ash dispersion. These trends are certainly favorable for immediate transport to Greenland. *Larsen* [1984] interpreted the tephra distribution and the presence of silicic tephra at the base or in the lower parts of the western deposits (i.e., a quicker deposition of the silicic tephra) as being indicative of southerly winds at the beginning of the eruption with a shift to a more counterclockwise direction during the eruption.

4.1.1. Volcanic aerosol record and implications.
Evidence of volcanic aerosol deposition on Greenland comes from the SO_4^{2-} record in the GISP2 core, but it is not a large signal. The 200-year period from 1000 to 1200 years ago (A.D. 800 to 1000) shows several small to moderate SO_4^{2-} spikes including the signal related to the Vatnaöldur (Settlement Layer) eruption (Figure 4a). The exception is the very large signal from the voluminous Icelandic Eldgjá eruption (Figure 4a) [*Zielinski et al.*, 1995]. Subannual sampling in the GISP2 core over the length of core thought to contain debris from the Vatnaöldur eruption shows elevated SO_4^{2-} concentrations beginning early in A.D. 877 and extending through the summer into the fall (Fig-
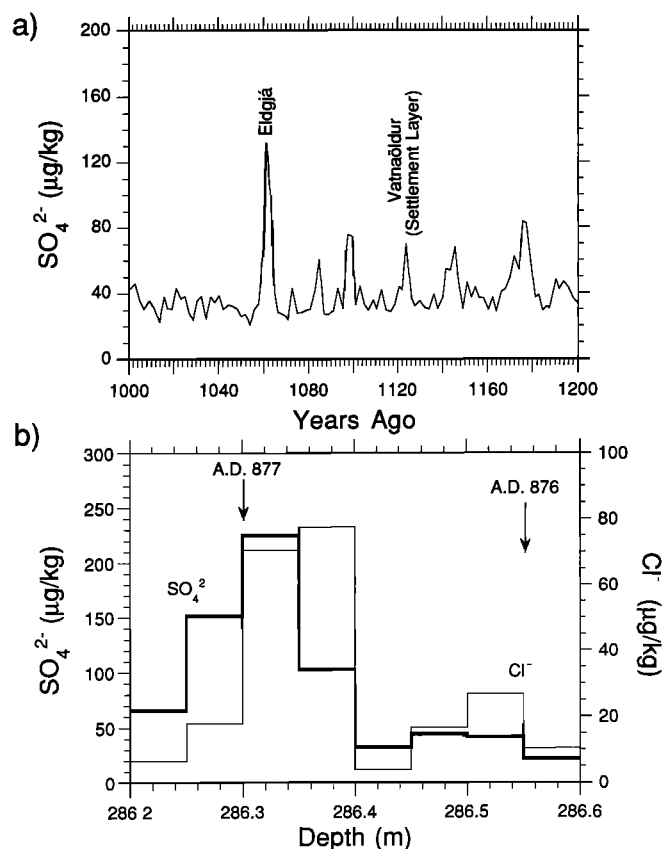

Figure 4. (a) Biyearly SO_4^{2-} concentrations for the 200-year period from 1000 to 1200 years ago (A.D. 1200-800) in the GISP2 core. SO_4^{2-} peak associated with deposition of aerosols from the eruption that produced the Settlement Layer (Iceland) is indicated as is the very large Icelandic Eldgjá eruption of ~A.D. 938 [*Zielinski et al.*, 1995]. (b) Detailed (subannual) SO_4^{2-} and Cl^- time series for the section of core containing aerosols from the eruption that produced the Settlement Layer. The section from 286.25 to 286.40 contained volcanic glass, as discussed in the text and on Figure 5. Arrows indicate depth of midsummer of year shown.

ure 4b). A spike in Cl^- occurs just prior to the increase in SO_4^{2-}. Volcanic SO_4^{2-} flux onto the ice sheet is calculated to be 17 kg/km² over the roughly 0.75 years of deposition. The biyearly sampling that included this event yielded a volcanic SO_4^{2-} flux of 13 kg/km² [*Zielinski*, 1995]. Considering the suggested wind pattern from the NW distribution of tephra on Iceland, it is probable that at least most of the early SO_4^{2-} deposition was from tropospheric transport. Thus the far-reaching atmospheric impact of this eruption was probably minimal. Detailed glaciochemical studies across this same section in the GRIP core showed a similar pattern to the SO_4^{2-} and Cl^- signals, but the age of the signal in the GRIP core is given as A.D. 871 [*Grönvold et al.*, 1995]. Nevertheless, the age of this layer with suggested error overlaps that of the GISP2 core (Table 1).

Table 1. Depths and Estimated Ages of Icelandic Tephra Layers Found in Both the GISP2 and GRIP Ice Cores

Tephra Layer[a] (Probable Source)	Depth, m[b]		Age (With Error)	
	GISP2	GRIP	GISP2	GRIP
Settlement Layer (Vatnaöldur)	286.25-286.40	269.22-269.50	A.D. 877 (± 4)	A.D. 871 (± 2)
Saksunarvatn ash (Grimsvötn)	1586.46-1586.49 1586.74-1586.76 1586.96-1586.97	1528.61-1529.01	10,318 (± 205)[c] 10,322 (± 205) 10,325 (± 205)	10,230 (± 60)[c]
Ash Zone Z2 (Torfajökull area, Katla)	2464.25-2464.30	2430.95-2430.98	52,682 (± 5000)[c]	~52,000[c]

[a]Name of equivalent ash layer that correlates to tephra found in the Summit ice cores.
[b]Depth of sampled section of ice containing tephra.
[c]Age in years before A.D. 2000. To convert to years before 1950, subtract 50 from this age.

4.1.2. Settlement Layer tephra and implications.

Verification of the source of the aerosol signal in each core comes from the presence of tephra that matches the bimodal composition of the magma erupted (Table 2, Figure 5) as found in terrestrial deposits in Iceland [*Grönvold et al.*, 1995]. Our findings thus provide a more closely limiting calendrical age for the eruption, that is within the mid-A.D. 870s (Table 1). By locating Settlement tephra in the Summit ice cores, we also provide insight into the source of a previously unknown tephra found in peat bogs in Northern Ireland [*Pilcher et al.*, 1995]. Pilcher et al. found tephra in a section of the bog that was radiometrically dated and calibrated to a calendar year of A.D. 860 ± 20. The mean composition of that tephra does not match well with the silicic component of the Settlement Layer ash (Table 2, Figure 5). Further, Pilcher et al. did not find the more basaltic tephra in the same sample. These results suggest that the tephra found in Northern Ireland bogs did not originate from the Vatnaöldur eruption despite a calibrated age that overlaps our ice-core age.

4.2. Saksunarvatn Ash (~10,300 Years Old)

The Saksunarvatn ash was first identified on the Faroe Islands [*Mangerud et al.*, 1986], southeast of Iceland, but more recently has been found at various sites in Iceland [*Björck et al.*, 1992; *Pétursson and Larsen*, 1992], Germany [*Merkt et al.*, 1993], and in marine sediments of the Norwegian sea [*Sjoholm et al.*, 1991]. Thus it has become an important early Holocene time marker in the North Atlantic region including its pres-

ence in the GRIP core [*Grönvold et al.*, 1995]. It is basaltic and easily differentiated from other late Pleistocene/early Holocene marker horizons in the North Atlantic (e.g., Vedde ash [*Mangerud et al.*, 1984, 1986]). The Grimsvötn volcanic system is believed to be the source of the Saksunarvatn ash. If the Grimsvötn system is the source, then it is likely the eruption was subglacial, which could contribute to its explosiveness and the presence of a visible ash layer on the summit of Greenland. It is the youngest visible ash layer in both the GISP2 and GRIP cores.

4.2.1. Volcanic aerosol record and implications.

The aerosol signal of the Saksunarvatn eruption in the GISP2 core is one of the three large SO_4^{2-} spikes over the 2000-year period from 10,000 to 12,000 years ago (Figure 6a). The difference in the estimated age of the Saksunarvatn ash and that of the I-THOL-1 tephra found in Lake Torfadalsvatn, Iceland [*Björck et al.*, 1992], is 300 years, meaning that the 140-year difference between the two youngest spikes on Figure 6a is similar enough to suggest that the second spike is related to the I-THOL-1 eruption (i.e., 10,454 ± 220 years ago). To the best of our knowledge, the largest spike in this section of core does not readily correlate to a known eruption.

Interestingly, a more detailed plot of the relationship between layers where tephra was found and the volcanic SO_4^{2-} record over the 11-m (17 year) section of core

Table 2. Average Major Oxide Composition of Tephra Found in the GISP2 and GRIP Ice Cores as Compared to Other Sources

Sample and Source[a]	SiO$_2$	TiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O
Settlement Layer								
GISP2 (6)	72.3 (1.0)	0.3 (0.1)	14.2 (0.6)	0.1 (0.4)	0.2 (0.1)	1.0 (0.1)	4.0 (1.1)	5.1 (0.4)
GRIP[b]	71.8	0.4	14.3	2.3	0.3	0.9	5.5	4.4
Ofaerugil[b]	72.0	0.3	14.5	2.3	0.2	0.9	5.3	4.5
Thingvallavatn[c] (5)	70.2 (0.9)	0.4 (0.2)	14.4 (0.1)	2.3 (0.1)	0.2 (0.02)	0.9 (0.1)	4.7 (0.2)	5.0 (0.1)
Northern Ireland[d] (17)	71.9 (1.4)	0.3 (0.03)	14.4 (0.6)	1.5 (0.1)	0.4 (0.03)	1.9 (0.1)	4.0 (0.5)	3.3 (0.6)
GISP2 (6)	52.0 (1.4)	1.5 (0.4)	13.8 (0.4)	14.0 (1.3)	6.1 (0.4)	11.0 (0.6)	1.1 (0.3)	0.4 (0.1)
GRIP[b]	50.6	1.9	13.7	12.5	6.7	10.9	2.7	0.3
Ofaerugil[b]	50.4	1.9	13.4	12.3	6.6	11.5	2.6	0.2
Northern Iceland[e]	50.4	2.0	13.4	13.1	6.4	11.4	2.5	0.2
Thingvallavatn[c] (8)	49.9 (0.9)	1.9 (0.3)	13.2 (0.4)	12.8 (0.5)	6.5 (0.2)	11.6 (0.2)	2.4 (0.2)	0.2 (0.2)
Saksunarvatn Ash								
GISP2 (A) (5)	50.2 (1.3)	3.1 (0.5)	13.1 (0.7)	14.7 (1.9)	5.0 (0.7)	10.0 (0.7)	3.5 (0.5)	0.4 (0.1)
GISP2 (B) (5)	49.8 (1.4)	3.4 (0.6)	12.8 (0.8)	15.1 (2.1)	5.0 (0.8)	10.1 (0.7)	3.3 (0.5)	0.5 (0.1)
GISP2 (C) (5)	50.1 (2.1)	3.0 (0.5)	13.4 (0.9)	14.0 (2.7)	5.4 (0.6)	9.9 (1.3)	3.8 (0.8)	0.4 (0.1)
GRIP[b]	49.1	2.8	13.2	15.2	5.6	10.1	2.7	0.4
Trofadalsvatn[f] (9)	48.9 (0.5)	2.8 (0.2)	13.4 (0.4)	13.8 (0.8)	6.0 (0.3)	10.6 (0.3)	2.6 (0.2)	0.4 (0.1)
Faroe Islands[g] (13)	49.2 (0.9)	2.0 (0.3)	12.9 (0.4)	13.7 (0.5)	5.6 (0.3)	9.3 (0.4)	⋯	0.4 (0.1)
Z2 Ash Layer								
GISP2 (A) (12)	76.5 (1.1)	0.3 (0.1)	12.8 (0.5)	3.3 (0.5)	0.2 (0.1)	0.4 (0.2)	2.3 (0.8)	4.3 (0.4)
GRIP[b] (5)	74.6 (0.4)	0.2 (0.04)	12.2 (0.2)	2.9 (0.3)	0.2 (0.1)	0.5 (0.2)	5.3 (0.2)	4.0 (0.2)
Dye 3[b]	74.0	0.2	11.9	2.3	0.1	0.4	5.3	4.1
Kirkjufell[b]	73.6	0.2	11.5	2.4	0.1	0.3	5.5	4.2
V23-81[b] (A)	74.2	0.1	11.7	2.4	0.1	0.4	5.3	4.0
GISP2 (B) (3)	49.1 (0.6)	4.0 (0.2)	14.3 (0.1)	15.9 (0.8)	4.1 (0.7)	9.5 (0.4)	2.2 (0.4)	1.0 (0.1)
V23-81[h] (B) (3)	46.1 (0.7)	4.5 (0.3)	12.7 (0.1)	15.1 (0.8)	5.6 (0.2)	9.3 (0.3)	1.9 (0.6)	1.0 (0.1)

Standard deviation in parentheses after percent by weight of individual oxide.

[a]Number of samples in parentheses after source of the analysis.

[b]*Grönvold et al.* [1995]. Most standard deviations not presented in this paper.

[c]*Haflidason et al.* [1992].

[d]*Pilcher et al.* [1995].

[d]*Pétursson and Larsen* [1992].

[f]*Björck et al.* [1992].

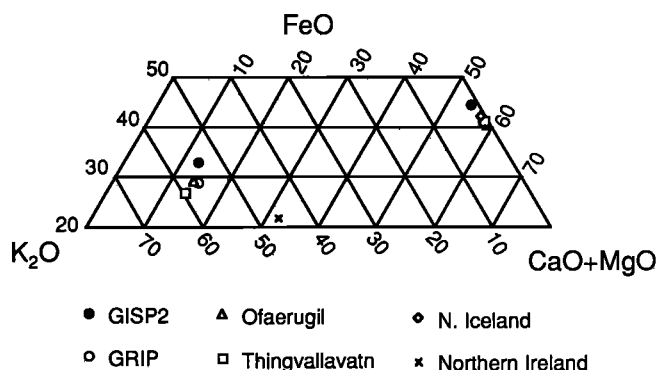[g]*Mangerud et al.* [1984].

[h]*Kvamme et al.* [1989].

Figure 5. FeO (total iron)-K_2O-CaO + MgO plot for the mean composition of individual glass shards for the eruption of Vatnaöldur, Iceland (which produced the Settlement Layer), as observed in the GRIP and GISP2 ice cores and various sites in Iceland. Compositions for the GRIP core and Icelandic sites are from *Grönvold et al.* [1995]. Mean composition of glass shards in a tephra layer (source unknown) found in Sluggan Bog, Northern Ireland, with an age of A.D. 860 ± 20 [from *Pilcher et al.*, 1995] is also shown for comparison.

containing Saksunarvatn tephra (Figure 6b) shows that the large SO_4^{2-} spike only corresponds to the dark visible layer that contained tephra (C in Figure 6b). The other two layers containing tephra (A and B in Figure 6b) were only cloudy in appearance with no visible dark tephra grains. Those two layers are not associated with a large SO_4^{2-} spike. One possibility is that this is a similar situation to that found in Antarctica ice cores, whereby some visible tephra layers were not associated with a large acid signal [*Palais and Kyle*, 1988]. The interpretation of that scenario was that volcanic glass neutralized the volcanic acid. In the case of the GISP2 core, this would mean that the tephra layers containing smaller sized grains (i.e., not visible to the naked eye) had the capability to neutralize the acid (maybe because of a greater surface area) but that neutralization did not occur where the glass shards were bigger. The second possibility is that more alkaline dust was deposited at the same time as the ash in the upper two tephra layers (A and B, Figure 6b), thereby neutralizing the volcanically produced acid.

The flux of volcanic SO_4^{2-} associated with the large spike in the detailed section of the GISP2 core is 88 kg/km^2 for the 2 years covered by this sample. This value is ~5 times that of the Vatnaöldur eruption of the mid-A.D. 870s and similar to that of the Icelandic Laki (A.D. 1783) and Eldgjá (A.D. 930s) eruptions [*Zielinski*, 1995], the two largest known historical fissure eruptions. These numbers imply that the Saksunarvatn eruption had a significant impact on northern hemisphere climate, as did the Laki [*Fiacco et al.*, 1994] and possibly the Eldgjá eruption [*Zielinski et al.*, 1995]. However, the large amount of ash deposition in Greenland associated with the aerosol signal of the Saksunarvatn eruption could be a result of a high degree of quick scavenging of the H_2SO_4 aerosols from the eruptive plume and
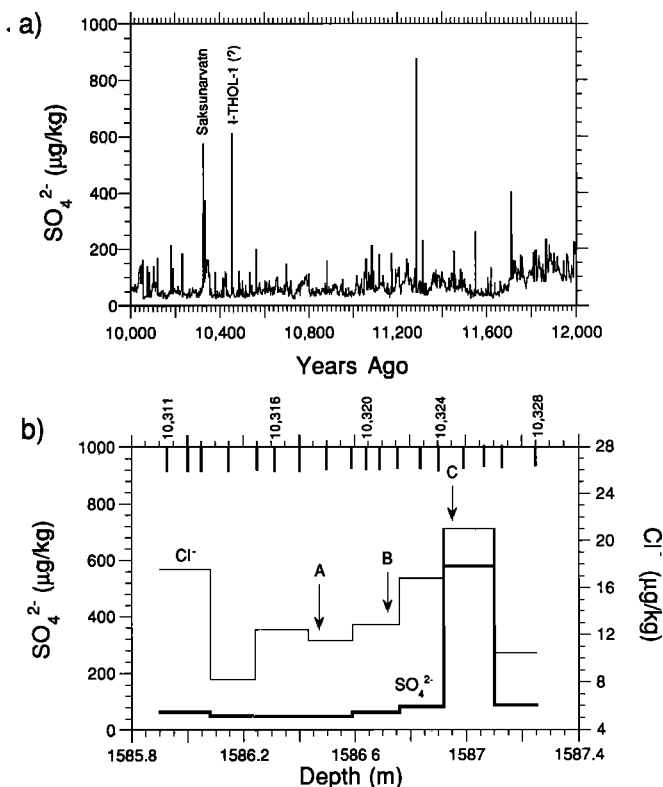

Figure 6. (a) Biyearly SO_4^{2-} concentrations for the 2000-year period from 10,000 to 12,000 years ago in the GISP2 core. All ages are years before A.D. 2000. Subtract 50 from these values to get years before 1950. SO_4^{2-} peak associated with deposition of aerosols from the eruption that produced the Saksunarvatn ash is indicated as is the peak that may be associated with the Icelandic eruption that produced the I-THOL-1 ash found in lake sediments in Iceland. (b) Biyearly SO_4^{2-} and Cl time series, shown in more detail, for the section of core that contains volcanic glass correlative to the Saksunarvatn ash. Tephra was found at the depths indicated by the arrows labeled A, B (cloudy bands), and C (visible dark band). Lines at top of Figure 6b represent the midsummer for the 18 years covered by the ~1.5 m shown here. Note that vertical scale is 5 times that of Figure 4a.

thus a smaller climatic impact compared to the Laki eruption.

4.2.2. Saksunarvatn tephra and implications. The compositions of the tephra (Figure 7) found in each of the two ice cores match very well with each other and with compositions from other sites in the North Atlantic region (Table 2, Figure 8). An interesting aspect of the nature of the tephra record in the GISP2 core is that tephra was found in layers spanning about 7 years of record. (The GRIP core sample was larger, so we are not able to determine if this scenario holds true in that core.) Intuitively, this implies that the Grimsvötn volcanic system was active at several times during this 7-year period. If this is true, then the characteristics of the Saksunarvatn eruption would have been comparable
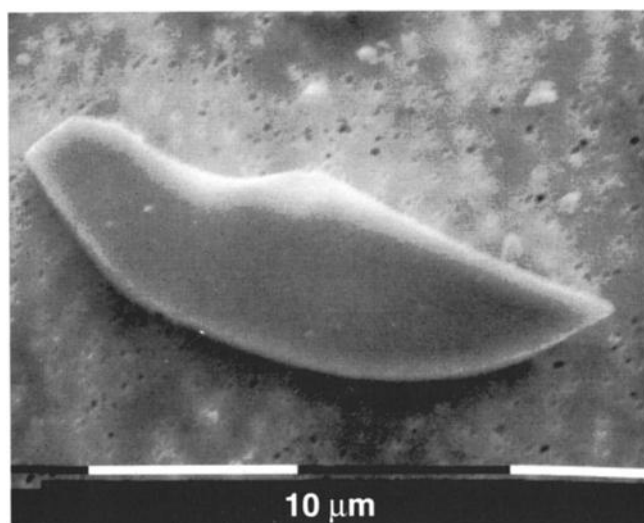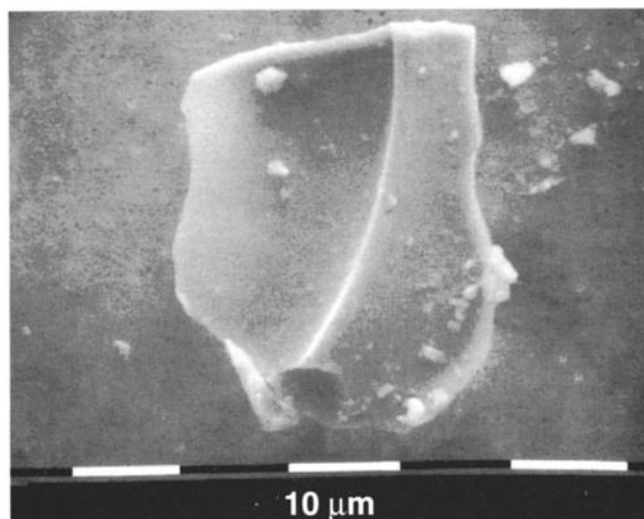
Figure 7. Microphotographs of typical basaltic glass shards found in layers A-C (Figure 6), 1586-1587 m in the GISP2 core.
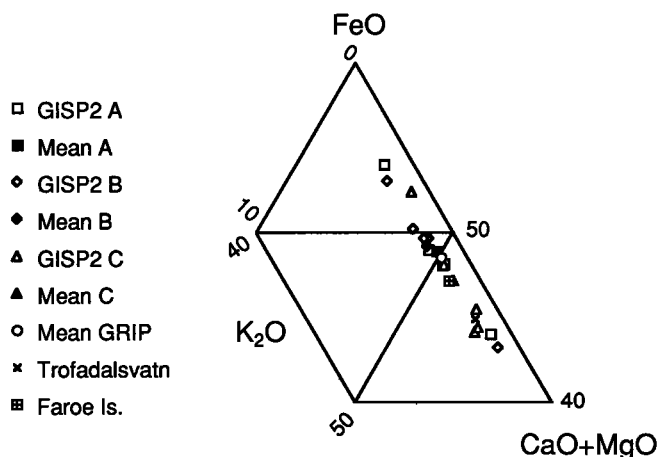

Figure 8. FeO (total iron)-K₂O-CaO + MgO plot showing the composition of individual glass shards and the mean composition for layers between 1586 and 1587 m in the GISP2 core and the mean composition of the equivalent layer in the GRIP core. Glass composition from each ice core matches with the eruption from the Grimsvötn system, Iceland, that produced the Saksunarvatn ash found on the Faroe Islands. Mean composition of the correlative ash layer from other sites in the North Atlantic region is also shown (as given by Grönvold et al. [1995]).

to an upscaled version of the Krafla eruptions between A.D. 1975 and 1984. However, we cannot rule out the possibility that the deposition of the two younger layers resulted from eolian deposition following storms that picked up fresh tephra grains in the years following the eruption. The lack of a volcanic SO_4^{2-} signal associated with the two younger layers (A and B in Figure 6b) could support the latter interpretation as opposed to the former whereby abundant alkaline dust may have been transported to Greenland at the same time as the tephra grains, resulting in neutralization of the acid signal. For now, we cannot say definitively either way.

In addition to identification of the Saksunarvatn ash in both ice cores, Grönvold et al. [1995] found tephra that matches that of the Vedde ash, another critical time marker in the North Atlantic region. We are now in the process of locating this same horizon in the GISP2 core. Similarly, we are searching in both cores for tephra from the German Laacher See eruption (11,000 ± 50 ¹⁴C

yr, ~12,920 years ago [Bogaard and Schmincke, 1985]). Identification of this tephra as well as that from other known eruptions during the final stages of deglaciation will provide the paleoclimatic community with unsurpassed isochrons for establishing environmental conditions in the North Atlantic region at this time of dramatic climatic shifts.

4.3. Ash Zone Z2 (~52,000 Years Old)

Many marine cores in the North Atlantic region contain a visible tephra layer, designated the Z2 ash zone, with an interpolated age around 57,500 years ago based on the deep-sea ¹⁸O record [e.g., Ruddiman and Glover, 1972; Kvamme et al., 1989; Bond et al., 1993]. In addition, a visible ash layer in the Dye 3 ice core, southern Greenland, was found to correlate to these ash layers in the deep marine cores, but the section of ice containing this layer is in the lower, disturbed parts of the Dye 3 core [Ram and Gayley, 1991]. This prevented a reliable improvement on dating of the Z2 layer using the Dye 3 findings. More recently, Grönvold et al. [1995] showed that a visible layer in the GRIP ice core also correlated to the rhyolitic component of the Z2 ash zone. Detailed dating of the GRIP core at that depth has yet to be undertaken, but the age of this tephra layer appears to be closer to 52,000 years ago. Thus this layer is a key marker horizon for correlation of paleoclimatic proxy records across the North Atlantic region during the middle of the last glacial cycle [Bond et al., 1993], and it is critical to obtain a firmer age for the eruption(s) and more thoroughly evaluate the eruption(s) responsible for this tephra layer.
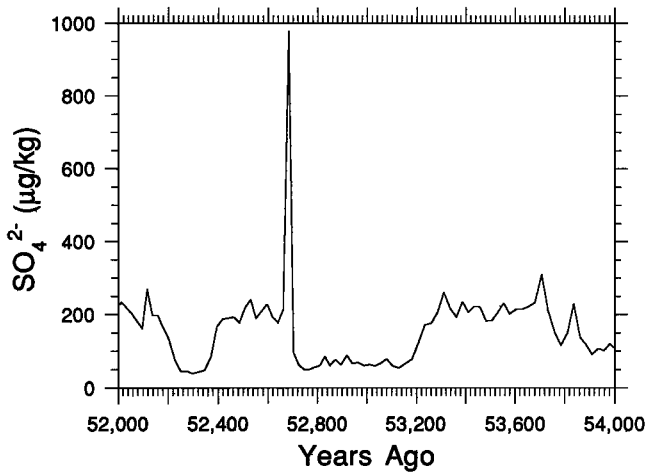
Figure 9. Time series of SO_4^{2-} concentrations for the 2000-year period from 52,000 to 54,000 years ago in the GISP2 core, emphasizing the large signal associated with the deposition of aerosols from the eruption(s) responsible for deposition of the Z2 ash layer equivalent in the GISP2 core. Ages are as in Figure 6. High SO_4^{2-} baseline values reflect colder conditions during glacial/stadial times, whereas low SO_4^{2-} baseline values reflect warmer conditions during interglacial/interstadial times. Note that vertical scale is twice that of Figure 4a.

4.3.1. Volcanic aerosol record and implications.

To obtain more information on the eruption(s) responsible for the Z2 ash layer, we evaluated the glaciochemistry and tephra found in the visible ash layer at the 2464.25- to 2464.30-m depth in the GISP2 core. The continuous SO_4^{2-} time series across the section of core between 52,000 and 54,000 years ago shows a very large spike corresponding to 52,680 ± 5000 years ago (Figure 9). Volcanic SO_4^{2-} flux for this signal is about 100 kg/km² over the 21 years represented by this sample, without taking into account layer thinning. Flux values would probably be an order of magnitude greater on an annual basis during the time of the eruption and correcting for thinning. Nevertheless, this is one of the larger volcanic signals in the core (Figure 1), but undoubtedly, there is a significant tropospheric component to the signal. As was probably the case for deposition of aerosols with Saksunarvatn tephra, the high SO_4^{2-} signal associated with the visible Z2 layer could be due in a large part to the absorption of H_2SO_4 aerosols onto tephra grains during the eruption. On the other hand, as we proposed for the eruption responsible for the Saksunarvatn ash, if just half of the aerosols produced during the Z2 volcanic event reached the stratosphere, there probably was a significant cooling of northern hemisphere climate during the years following the eruption(s). Also, the timing of the eruption(s) comes at the beginning of the roughly 200-year stadial event (as indicated by high SO_4^{2-} baseline concentrations) between ~52,600 and 52,400 years ago. As we stated earlier, the timing of these eruptions may be a direct result of increased crustal stress conditions in the
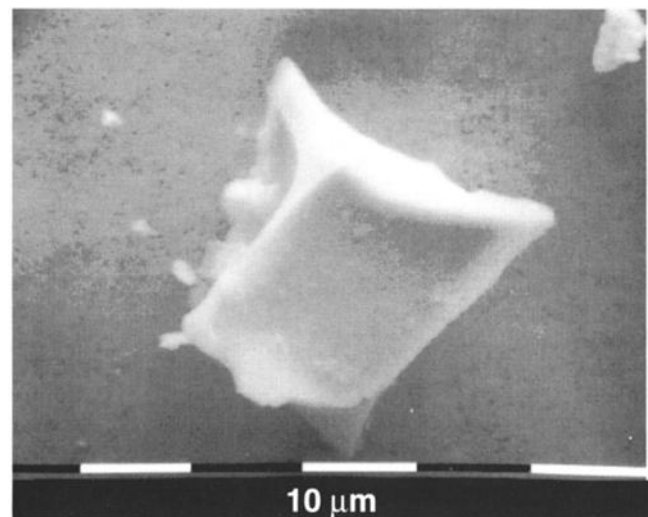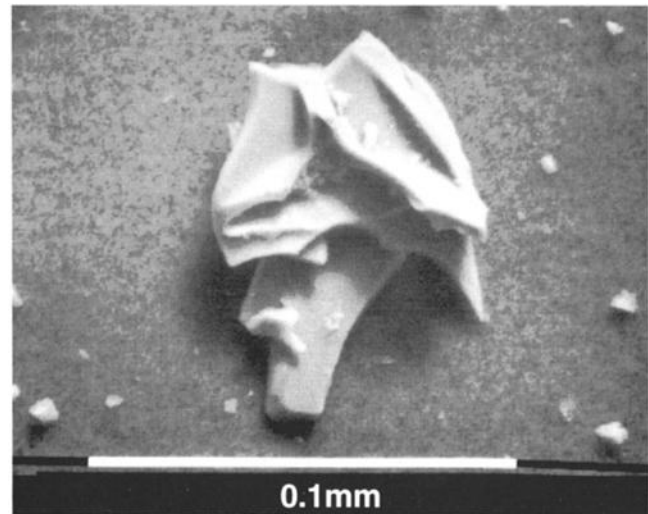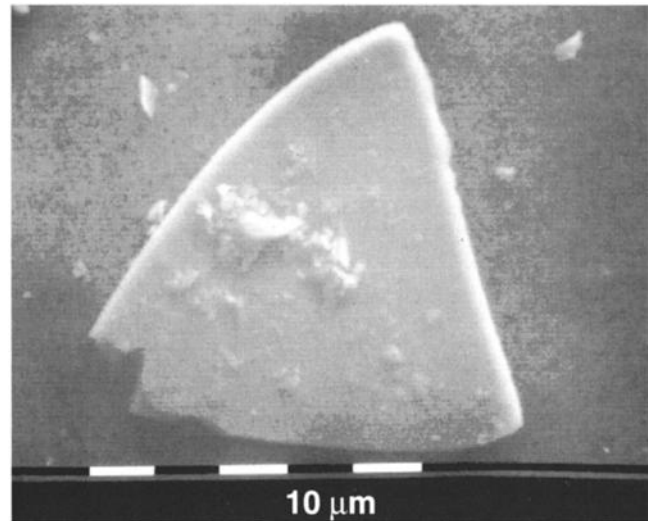

Figure 10. Microphotographs of typical glass shards found in the visible ash layer at 2464.25-2464.30 m in the GISP2 core. Note the two different morphologies that characterize the rhyolitic glass (top two photographs); morphology of the basaltic grains (bottom photograph) is not variable.
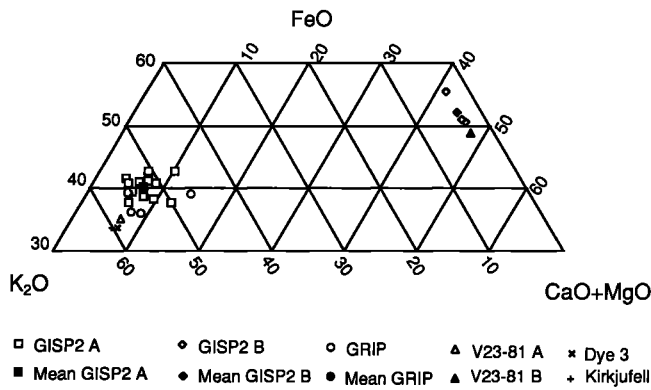
□ GISP2 A   ◇ GISP2 B   ○ GRIP   △ V23-81 A   ✕ Dye 3
■ Mean GISP2 A   ◆ Mean GISP2 B   ● Mean GRIP   ▲ V23-81 B   ✦ Kirkjufell

Figure 11. FeO (total iron)-K_2O-CaO + MgO plot showing the composition of individual glass shards and mean compositions from 2464.25-2464.30 m in the GISP2 core and the mean composition of the equivalent layer in the GRIP core. Glass composition from each ice core closely matches that of the Z2 ash layer found in marine sediment cores from the North Atlantic region. Mean compositions of the ash layer found in the Dye 3, Greenland ice core, V23-81 marine core, and the Kirkjufell region of Iceland are also shown (as given by *Grönvold et al.* [1995]).

Iceland region related to rapid isostatic adjustments at the close of the ~10,000-year glacial period that ended about 53,200 years ago and the small stadial event beginning around 52,600 years ago.

4.3.2. Z2 layer tephra and implications. We identified two distinctly different tephra populations in the 5-cm-thick visible layer in the GISP2 core (Figure 10). The most abundant population is rhyolitic (glass A, Table 2, Figure 11), with two distinct morphologies characterizing individual shards: one having a distinct flat, bubble-wall morphology, and the second being more blocky and vesicular (Figure 10). The second population is basaltic (glass B, Table 2, Figure 11), although only 5% of the grains are of this composition. The brown color of the basaltic grains under refracted light in a standard optical scope contrasted greatly with the clear appearance of the rhyolitic grains. Composition of the rhyolitic glass very closely matches with that from the GRIP core and other deposits thought to be correlative to the Z2 layer. However, the basaltic glass was not observed in the GRIP core, which could be a function of the apparently small quantity deposited in the Summit region. The slight difference between the basaltic compositions from the GISP2 core and those from deep-sea core V23-81 (B glasses, Figure 11), as well as the slight differences between the GISP2/GRIP and other rhyolitic glasses, are very likely a function of the EDS technique used on the GISP2 particles and the WDS used in the analysis of tephra from the deep-sea cores.

The possible source of the Z2 layer has been briefly discussed by *Grönvold et al.* [1995] and in slightly more detail by *Kvamme et al.* [1989], who compared individual shard compositions from a series of marine

sediment cores in the North Atlantic. Several possible sources have been proposed for this layer. One possibility is the Torfajökull region of southern Iceland, given the similarity of the mean composition of the rhyolitic component of the ash layer in the ice and marine sediment cores with that from the Kirkjufell formation in Iceland [*Grönvold et al.*, 1995] (Figure 11). However, *Kvamme et al.* [1989] suggested that there could have been multiple eruptions responsible for deposition of the Z2 layer based on the slightly different compositions of the basaltic components found within the Z2 zone. These possible sources include the major volcanic zones of the Grimsvötn and Veidivötn systems as well as the major volcanoes of Hekla and Katla. The basis for the differentiation is covariation between TiO_2 and FeO/MgO compositions with higher FeO/MgO ratios (i.e., between 2.5 and 4) being more characteristic of the Hekla and Katla volcanoes. Of those two, Katla has the higher FeO/MgO ratio for a given TiO_2 composition. FeO/MgO ratios between 3 and 4 for the basaltic component in the GISP2 core may support the idea that two simultaneous eruptions were responsible for the Z2 ash zone, that is, eruptions from both the Torfajökull area and Katla volcano.

5. Conclusions

We presented three different records from the recently collected GISP2 and GRIP ice cores, Summit, Greenland, useful in the evaluation of past volcanism. The 110,000-year time series of volcanic aerosol deposition in the GISP2 core, as developed from continuous SO_4^{2-} measurements, suggests a very strong relationship between explosive volcanism and the effects of climate change. The greatest number of signals and the overall greatest magnitude signals occur from 6000 to 17,000 years ago, during and after the final stages of deglaciation. This finding supports the concept that increases in the stress placed on magma chambers with isostatic adjustment to glacial unloading may be sufficient to enhance volcanic activity particularly in the midlatitudes of the northern hemisphere (i.e., Iceland, North Pacific Rim). Further, the coincident increase in volcanism during this time period with the rapid rise in sea level during deglaciation lends further credence to previous ideas that crustal stresses associated with the increase in crustal loading from greater meltwater flow into ocean basins can significantly increase explosive volcanism in island arc and coastal volcanic systems. Slightly lower numbers of lesser magnitude signals occur 27,000-36,000 and 79,000-85,000 years ago, leading up to the last glacial maximum and the initial buildup of ice prior to the beginning of the last glacial period, respectively. Moreover, some of the stadial/interstadial transitions are marked by the presence of a large, single volcanic signal or set of signals. These relationships further substantiate a strong volcanism-climate feedback system and a strong linkage among the lithosphere-hydrosphere (cryosphere and oceans)-atmosphere.

Comparisons between the ECM record of volcanism and the volcanic SO_4^{2-} record for the Holocene showed that about 50% of the larger signals are found in both records. However, most of the differences in this case could be tied to the thresholds chosen for demarcating the presence of a signal at a particular time. In our case it was a single threshold for each time series. Other causes for the discrepancy can be the presence of other volcanic acids (e.g., HCl and HF) and different sources for the SO_4^{2-}. Although a better relationship between these two measurements was expected, these results show that we still do not have a complete understanding of the variability of volcanic signals recorded in ice cores.

Finally, we evaluated the tephra deposited from three separate eruptions recorded in both ice cores. Tephra was found in each core with compositions similar to that of the Icelandic Vatnaöldur eruption (mid-A.D. 870s) that produced the Settlement Layer in Iceland, the Saksunarvatn ash (thought to originate from the Grimsvötn volcanic system about 10,300 years ago), and the Z2 ash ($\sim$52,700 years ago) found in marine cores throughout the North Atlantic region. The composition of all of these tephras closely matched that of samples from either terrestrial deposits or marine sediment cores. The presence in the GISP2 core of both a rhyolitic and basaltic glass in the section correlative to the Z2 ash and the composition of the basaltic component appear to lend support to the possibility that two simultaneous eruptions in Iceland produced the Z2 ash zone. Our findings suggest that both the Torfajökull area and the Katla volcano are possible sources for this ash layer. By identifying all three of these ash layers in each of the two ice cores, we now are able to identify absolute, instantaneous time lines for correlation between the two cores and especially for correlation of the ice-core proxy climatic records with those from marine cores and terrestrial records.

In conclusion, this paper provides several illustrative examples of how ice cores are used in paleovolcanic and paleoclimatic research. The limitations in the use of volcanic records produced from single ice cores must be acknowledged; however, the ability to match the volcanic records developed from two (as herein) or more cores increases the confidence one has in their reliability. The greatest advantages of these records are their length (110,000 years in these cases), high resolution (subannual to annual to decadal), and preservation of both the aerosol and silicate (tephra) components of past eruptions. Thus, ice cores provide the most comprehensive means available to reconstruct chronologies of past volcanism, to evaluate the volcanism-climate system including both the climatic impact of volcanism and the possible impact that the effects of changing climatic conditions have on volcanism, and to definitively correlate proxy records developed from ice cores with those developed from marine sediment cores and terrestrial records containing the same tephra layers.

References

Björck, S., O. Ingólfsson, H. Haflidason, M. Hallsdóttir, and N.J. Anderson, Lake Tofradalsvatn: A high resolution record of the North Atlantic ash zone 1 and the last glacial-interglacial environmental changes in Iceland, *Boreas, 21*, 15-22, 1992.

Bogaard, P.V., and H.U. Schmincke, Laacher See tephra: A widespread isochronous late Quaternary tephra layer in central and northern Europe, *Geol. Soc. Am. Bull., 96*, 1554-1571, 1985.

Bond, G., W. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel, and G. Bonani, Correlations between climate records from North Atlantic sediments and Greenland ice, *Nature, 365*, 143-147, 1993.

Buck, C.F., P.A. Mayewski, M.J. Spencer, S. Whitlow, M.S. Twickler, and D. Barrett, Determination of major ions in snow and ice cores by ion chromatography, *J. Chromatogr., 594*, 225-228, 1992.

Castagnoli, G.C., et al., Evidence for enhanced [10]Be deposition in Mediterranean sediments 35 Kyr BP, *Geophys. Res. Lett., 22*, 707-710, 1995.

Chesner, C.A., W.I. Rose, A. Deino, R. Drake, and J.A. Westgate, Eruptive history of Earth's largest Quaternary caldera (Toba, Indonesia) clarified, *Geology, 19*, 200-203, 1991.

Clausen, H.B., and C.U. Hammer, The Laki and Tambora eruptions as revealed in Greenland ice cores from 11 locations, *Ann. Glaciol., 10*, 16-22, 1988.

Clausen, H.B., C.U. Hammer, C.S. Huidberg, D. Dahl-Jensen, J.P. Steffensen, J. Kipfstuhl, and M. Legrand, 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.*, this issue.

Delmas, R.J., S. Kirchner, J.M. Palais, and J.R. Petit, 1000 years of explosive volcanism recorded at the South Pole, *Tellus, Ser. B, 44*, 335-350, 1992.

Fiacco, R.J., Jr., J.M. Palais, M.S. Germani, G.A. Zielinski, and P.A. Mayewski, Characteristics and possible source of a 1479 A.D. volcanic ash layer in a Greenland ice core, *Quat. Res., 39*, 267-273, 1993.

Fiacco, R.J., Jr., T. Thordarson, M.S. Germani, S. Self, J.M. Palais, S. Whitlow, and P. Grootes, 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, 1994.

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

Grove, E.W., Deglaciation–A possible triggering mechanism for recent volcanism, paper presented at Andean and Antarctic Volcanology Problems, Int. Assoc. Volcanol. Symp., Santiago, Chile, 1976.

Haflidason, H., G. Larsen, and G. Olafsson, The recent sedimentation history of Thingvallavatn, Iceland, *Oikos, 64*, 80-95, 1992.

Hammer, C.U., Acidity of polar ice cores in relation to absolute dating, past volcanism and radio-echoes, *J. Glaciol., 25*, 359-372, 1980.

Hammer, C.U., H.B. Clausen, and W. Dansgaard, Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, *Nature, 288*, 230-235, 1980.

Kvamme, T., J. Mangerud, H. Furnes, and W.F. Ruddiman, Geochemistry of Pleistocene ash zones in cores from the North Atlantic, *Nor. Geol. Tidsskr., 69*, 251-272, 1989.

Kyle, P.R., P.A. Jezek, E. Mosley-Thompson, and L.G. Thompson, Tephra layers in the Byrd Station ice core and the Dome C ice core, Antarctica, and their climatic implications, *J. Volcanol. Geotherm. Res., 11*, 29-39, 1981.

Larsen, G., Recent volcanic history of the Veidivötn fissure swarm, southern Iceland–An approach to volcanic risk assessment, *J. Volcanol. Geotherm. Res., 22*, 33-58, 1984.

Legrand, M., and R.J. Delmas, A 220-year continuous record of volcanic H_2SO_4 in the Antarctic Ice Sheet, *Nature, 327*, 671-676, 1987.

Mangerud, J., S.E. Lie, H. Furnes, I.L. Kristiansen, and L. Lømo, A Younger Dryas ash bed in western Norway, and its possible correlations with tephra in cores from the Norwegian Sea and the North Atlantic, *Quat. Res., 21*, 85-104, 1984.

Mangerud, J., H. Furnes, and J. Jóhansen, A 9000-year-old ash bed on the Faroe Islands, *Quat. Res., 26*, 262-265, 1986.

Matthews, R.K., Tectonic implications of glacio-eustatic sea level fluctuations, *Earth Planet. Sci. Lett., 5*, 459-462, 1969.

Mayewski, P.A., G. Holdsworth, M.J. Spencer, S. Whitlow, M. Twickler, M.C. Morrison, K.K. Ferland, and L.D. Meeker, Ice core sulfate from three northern hemisphere sites: Source and temperature forcing implications, *Atmos. Environ., Part A, 27*, 2915-2919, 1993.

Mayewski, P.A., L.D. Meeker, S. Whitlow, M.S. Twickler, M.C. Morrison, P.M. Grootes, G.C. Bond, R.B. Alley, D.A. Meese, and T. Gow, Changes in atmospheric circulation and ocean ice cover over the North Atlantic region during the last 41,000 years, *Science, 263*, 1747-1751, 1994.

Mayewski, P.A., L.D. Meeker, M.S. Twickler, S. Whitlow, Q. Yang, and M. Prentice, Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series, *J. Geophys. Res.*, this issue.

McGuire, W.J., C.R. Firth, R.J. Howarth, A.D. Pullen, S.J. Saunders, I.S. Stewart, and C. Vita-Finzi, Increased explosive volcanic activity due to late Quaternary sea-level changes: A potential climate modifier?, paper presented at Geological Society of London Annual Meeting, London, 1995.

Meese, D.A., R.B. Alley, A.J. Gow, P. Grootes, P.A. Mayewski, M. Ram, K.C. Taylor, and G.A. Zielinski, Preliminary depth/age scale of the GISP2 core, *CRREL Spec. Rep. 94-1*, Cold Reg. Res. and Eng. Lab., Hanover, N.H., 1994.

Merkt, J., H. Muller, W. Knabe, P. Muller, and T. Weiner, The early Holocene Saksunarvatn tephra found in lake sediments in NW Germany, *Boreas, 22*, 93-100, 1993.

Moore, J.C., E.W. Wolff, H.B. Clausen, and C.U. Hammer, The chemical basis for the electrical stratigraphy of ice, *J. Geophys. Res., 97*, 1887-1896, 1992.

Nakada, M., and H. Yokose, Ice age as a trigger of active Quaternary volcanism and tectonism, *Tectonophysics, 212*, 321-329, 1992.

Palais, J.M., and P.R. Kyle, Chemical composition of ice containing tephra layers in the Byrd Station ice core, Antarctica, *Quat. Res., 30*, 315-330, 1988.

Palais, J.M., K. Taylor, P.A. Mayewski, and P. Grootes, Volcanic ash from the 1362 A.D. Oraefajökull eruption (Iceland) in the Greenland Ice Sheet, *Geophys. Res. Lett., 18*, 1241-1244, 1991.

Palais, J.M., M.S. Germani, and G.A. Zielinski, 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, 1992.

Paterne, M., and F. Guichard, Triggering of volcanic pulses in the Campanian area, South Italy, by periodic deep magma influx, *J. Geophys. Res., 98*, 1861-1873, 1993.

Pétursson, H.G., and G. Larsen, An early Holocene basaltic tephra bed in north Iceland, a possible equivalent to the Saksunarvatn ash bed, paper presented at 20th Nordic geological winter meeting, Reykjavick, Iceland, 1992.

Pilcher, J.R., V.A. Hall, and F.G. McCormac, Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats, *Holocene, 5*, 103-110, 1995.

Ram, M., and R.I. Gayley, Long-range transport of volcanic ash to the Greenland Ice Sheet, *Nature, 349*, 401-404, 1991.

Rampino, M.R., and S. Self, Climate-volcanism feedback and the Toba eruption of ~74,000 years ago, *Quat. Res., 40*, 269-280, 1993.

Rampino, M.R., S. Self, and R.W. Fairbridge, Can rapid climatic change cause volcanic eruptions?, *Science, 206*, 826-829, 1979.

Rampino, M.R., S. Self, and R.B. Stothers, Volcanic winters, *Annu. Rev. Earth Planet. Sci., 16*, 73-99, 1988.

Rind, D., and J. Overpeck, Hypothesized causes of decade-to-century-scale climate variability: Climate model results, *Quat. Sci. Rev., 12*, 357-374, 1993.

Robock, A., and M.P. Free, Ice cores as an index of global volcanism from 1850 to the present, *J. Geophys. Res., 100*, 11,549-11,567, 1995.

Rose, W.I., Jr., Scavenging of volcanic aerosol by ash: Atmospheric and volcanologic implications, *Geology, 5*, 621-624, 1977.

Ruddiman, W.F., and L.K. Glover, Vertical mixing of ice-rafted volcanic ash in North Atlantic sediments, *Geol. Soc. Am. Bull., 83*, 2817-2836, 1972.

Self, S., M. Rampino, and J.J. Barbera, The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures, *J. Volcanol. Geotherm. Res., 11*, 41-60, 1981.

Sheridan, P.J., R.C. Schnell, D.J. Hofmann, and T. Deshler, Electron microscope studies of Mt. Pinatubo aerosol layers over Laramie, Wyoming during summer 1991, *Geophys. Res. Lett., 19*, 203-206, 1992.

Sigvaldason, G.E., K. Annertz, and M. Nilsson, Effect of glacier loading/deloading on volcanism: Postglacial volcanic production rate of the Dyngjufjöll area, central Iceland, *Bull. Volcanol., 54*, 385-392, 1992.

Sjoholm, J., H.P. Sejrup, and H. Furnes, Quaternary volcanic ash zones on the Iceland plateau, southern Norwegian Sea, *J. Quat. Sci., 6*, 159-173, 1991.

Taylor, K., R. Alley, J. Fiacco, P. Grootes, G. Lamorey, P. Mayewski, and M.J. Spencer, Ice-core dating and chemistry by direct-current electric conductivity, *J. Glaciol., 38*, 325-332, 1992.

Wolff, E.W., J.C. Moore, H.B. Clausen, C.U. Hammer, J. Kipfstuhl, and K. Fuhrer, Long-term changes in the acid and salt concentrations of the Greenland Ice Core Project ice core from electrical stratigraphy, *J. Geophys. Res., 100*, 16,249-16,263, 1995.

Zielinski, G.A., Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the GISP2 Greenland ice core, *J. Geophys. Res.*, *100*, 20,937-20,955, 1995.

Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S. Whitlow, M.S. Twickler, M. Morrison, D. Meese, R.B. Alley, and A.J. Gow, Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system, *Science, 264*, 948-952, 1994.

Zielinski, G.A., M.S. Germani, G. Larsen, M.G.L. Baillie, S. Whitlow, M.S. Twickler, and K. Taylor, Evidence of the Eldgjá (Iceland) eruption in the GISP2 Greenland ice core: Relationship to eruption processes and climatic conditions in the tenth century, *Holocene, 5*, 129-140, 1995.

Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S. Whitlow, and M. Twickler, A 110,000-year record of explosive volcanism from the GISP2 (Greenland) ice core, *Quat. Res., 45*, 109-118, 1996a.

Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S. Whitlow, M. Twickler, and K. Taylor, Potential atmospheric impact of the Toba mega-eruption ~71,000 years ago, *Geophys. Res. Lett., 23*, 837-840, 1996b.

M. S. Germani, MVA, Inc., 136 Shore Drive #200, Burr Ridge, Illinois 60521.

Karl Grönvold, Nordic Volcanological Institute, University of Iceland, IS-101 Reykjavik. (email: karl@norvol.hi.is)

P. A. Mayewski, L. D. Meeker, M. S. Twickler, S. Whitlow, and G. A. Zielinski, Climate Change Research Center, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824. (email: p_mayewski@unh.edu; ldm@math.unh.edu; mark.twickler@unh.edu; siw@unh.edu; Greg.Zielinski@unh.edu)

Kendrick Taylor, Desert Research Institute, University of Nevada, Reno, Nevada 89506. (email: kendrick@maxey.unr.edu)