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# Visual-stratigraphic dating of the GISP2 ice core: Basis, reproducibility, and application

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**Abstract.** Annual layers are visible in the Greenland Ice Sheet Project 2 ice core from central Greenland, allowing rapid dating of the core. Changes in bubble and grain structure caused by near-surface, primarily summertime formation of hoar complexes provide the main visible annual marker in the Holocene, and changes in "cloudiness" of the ice correlated with dustiness mark Wisconsinan annual cycles; both markers are evident and have been intercalibrated in early Holocene ice. Layer counts are reproducible between different workers and for one worker at different times, with 1% error over century-length times in the Holocene. Reproducibility is typically 5% in Wisconsinan ice-age ice and decreases with increasing age and depth. Cumulative ages from visible stratigraphy are not significantly different from independent ages of prominent events for ice older than the historical record and younger than approximately 50,000 years. Visible observations are not greatly degraded by "brittle ice" or many other core-quality problems, allowing construction of long, consistently sampled time series. High accuracy requires careful study of the core by dedicated observers.

## 1. Introduction

Analyzing visible layers is among the oldest of ice sheet stratigraphic techniques [e.g., *Benson* 1962; *Langway* 1967; *Gow* 1968b]. It is based on the simple observation that summer snow and winter snow look different. This difference in appearance arises from the physical reality that the properties of near-surface snow are affected by atmospheric conditions and radiative fluxes, which change seasonally.

"Correctness" of visible stratigraphy in dating accumulated snow has had a mixed record, ranging from high accuracy to significant errors [e.g., *Clausen* and *Dansgaard,* 1977]. This probably has multiple origins, including variations in visibility of strata, degree of seasonality of strata, accumulation rate, and, we strongly suspect, knowledge/ability of observers. Because visible observation is so easy (almost anyone can look at snow or ice) there may have been a wide diversity in training and experience, especially in the early traversing days, such that some observers may have lacked the expertise needed for highly accurate observations whereas others certainly were masters of the art. In light of this mixed record, *Hammer et al.,* [1978] estimated that visible stratigraphy is proven to ages of no more than 200 years with accuracy of 10%.

The advantages of visible stratigraphy for ice-core dating include the ease with which it is accomplished, the rapid dating which allows adjustment of sampling schemes in real time during core processing, the adaptability of the method in brittle ice or under other changes in ice quality, and the strong physical basis of the seasonal signal. Before application to the Greenland Ice Sheet Project 2 (GISP2) core, however, it was necessary to demonstrate that visible stratigraphy is sufficiently accurate to be useful and to characterize that accuracy better. We undertook a multicomponent study which included process studies of the origin of visible strata (section 2.1), regional monitoring of the occurrence and timing of visible strata using passive-microwave data (section 2.2), studies of physical processes in the ice that might affect the visible strata (section 2.3), and a variety of comparisons to other annual indicators, to marker events such as volcanic fallout, and to repeat counts by various analysts (section 5). The techniques used are described in sections 3 and 4. We believe visible stratigraphy provides dates for theGISP2 core that are accurate to within roughly 1% in the Holocene and within about 5% in the Wisconsinan ice age to roughly 40-50 kyr B.P. (thousand years before the year 1950).

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## 2. Basis of Visible Stratigraphy

### 2.1. Physical Processes of Formation of the Holocene Hoar Signal

One can see many things in an ice core. High concentrations of windblown or basally derived dust or of volcanic ash are easily visible to the eye [e.g., *Gow and Williamson,* 1976]. Melt layers appear in otherwise bubbly ice as glassylooking, bubble-free or nearly bubble-free zones [*Langway*, 1967; *Alley and Anandakrishnan*, 1995]. In the GISP2 core, forest-fire-fallout layers containing abundant ammonium, organic acids, and soot [*Legrand et al.*, 1992; *Whitlow et al.*, 1994; *Chylek et al.*, 1995; *Taylor et al.*, 1996] often are evident as fine-grained, fine-bubbled, faintly greenish or darkish layers. In ice from glacial times, "cloudy bands", which correlate with abundant dust and lowered electrical conductivity [*Taylor et al.*, 1993; *Kipfstuhl and Thorsteinsson*, 1993, *Ram et al.*, 1995] are the most prominent markers. Also, distortion of visible layering or of bubbles can indicate flow inhomogeneity and potential disruption of stratigraphic continuity [e.g., *Fitzpatrick* 1994; *Alley et al.*, 1995].

In Holocene ice and firn at GISP2, the most useful and prominent visible variations are caused by changes in bubble and grain sizes which in turn affect light transmission and reflection. These are most evident in snow pits, as layers from roughly 1 mm to several centimeters in thickness, which group into larger patterns forming annual cycles of roughly 50-75 cm length. During transformation of snow to ice, compaction and other diagenetic processes reduce the contrast between adjacent layers while reducing their thickness, but leave a weak signal of individual layers at the millimeter-centimeter scale and a clear annual signal at roughly 24 cm thickness. Strain thinning progressively reduces the thickness of these layers, but they remain visible as deep as bubbles are common in the core (roughly 1300-1400 m or roughly 8000 years). In deeper ice, clathrates have replaced bubbles [Gow et al., this issue], but progressive exsolution of the clathrates to form bubbles during core storage returns nearly the same signal as observed in shallower ice, at least for the Holocene.

Snow pit observations show that wintertime snow is more homogeneous than summertime snow. Nonetheless, in the subtle layering of winter snow one often can observe evidence of wind scouring, buried sastrugi, etc. Occasionally, poorly developed depositional depth-hoar layers may be present [see *Alley*, 1988], but they are not likely to be confused with well-developed, diagenetic or polygenetic hoar complexes primarily from the summer period of mid-June to late August [*Shuman et al.*, this issue]. Note that timing of accumulation in snow pits can be obtained in various ways; that of *Shuman et al.*, [1995] of comparing isotope/depth curves against temperature/time curves from instrumental observations is one useful technique. There is little or no ambiguity in our assignment of snow to summer or nonsummer in GISP2 snow pits.

Summer layers are characterized by coarse-grained, low-density depth hoar, often alternating with higher-density, finer-grained accumulation including wind slabs. We have observed the formation of several depth-hoar/wind-slab couplets during summers [*Alley et al.*, 1990; *Shuman and Alley*, 1993; *Shuman et al.*, 1993]. High densities and fine grain sizes in wind slabs are developed by snowfall from synoptic systems (storms) that penetrate to the Greenland summit [see Shuman et al., this issue]. During fair weather between storms, the Sun shines on the snow surface. Direct temperature measurements show that the Sun can warm the upper centimeter of the snow by as much as 4° to 5°C compared to conditions immediately above or below [*Alley et al.*, 1990]. Vapor diffusing out of this near-surface layer migrates primarily upward to the free atmosphere but also downward into deeper layers. The resultant mass loss produces low snow densities in the near surface. During rapid vapor flux, large, faceted crystals also grow in the low-density layers [Colbeck, 1982]. The result is a depth-hoar layer, formed within the upper 1 to several centimeters. Loss of at least 1/3-1/2 the initial mass is probable [*Alley et al.*, 1990]. (Densification also occurs during solar heating, causing the mass loss to be larger than indicated by the observed density decrease of 1/3 to 1/2.)

We have often observed that the warm depth-hoar-generating days occur during times of light wind and high atmospheric pressure over the GISP2 site [Shuman et al., this issue]. Radiative cooling at night can lead to fog and to hoar growth on all natural and artificial surfaces. This produces a surface hoar above the depth-hoar layer [*Alley et al.*, 1990; *Shuman and Alley*, 1993; *Bergin et al.*, 1995; *Shuman et al.*, this issue]. We refer to this combined surface-hoar/depth-hoar layer as a hoar complex.

One might expect that such low-density complexes would be weak and have poor preservation potential. In fact, we observed that a storm with 10 m/s or greater wind velocity which occurs at the end of a hoar-formation period will leave much of a hoar complex intact, often beneath a wind-packed crust, even in regions without snow deposition during the wind event. Thus these low-density hoar complexes have excellent preservation potential (Figure 1). Our observations also show that well-developed hoar layers that undergo gravitational collapse during "firn quakes" remain easily recognizable as hoar owing to persistence of coarse grains and to incompleteness of collapse.

## 2.2 Monitoring of Hoar Formation

We have conducted field monitoring of development and burial of several hoar complexes over multiple years at the GISP2 site [*Alley et al.*, 1990; *Shuman and Alley*, 1993; *Shuman et al.*, 1993; *Shuman et al.*, this issue]. This proves to be a tedious process. Extreme care must be taken to insure identification of the same layer over successive days. Even mild snow drifting or light snowfall can confuse the sampling. Simply returning to the same place and resampling the surface is unlikely to follow the time evolution of a given snow layer. Many possible tracers (dyes, plastic sheets, etc.) should be avoided because they alter the physical setting.

Our sampling scheme begins with widespread presampling of the surface, to characterize the areal variability of the snow stratigraphy. We then pick a well-characterized, often relatively homogeneous region and observe it more frequently than the time scale of physical changes (observations typically twice/day, with some observations as frequently as once every 1-2 hours). Samples for density and isotopic or chemical analysis are taken relative to widespread stratigraphic markers; wind crusts or wind slabs from previous snowfall have been useful.

This level of detailed observation is practicable for a few days or weeks at a single site, but not for regional studies. Fortunately, the process of hoar-complex formation has a clear passive-microwave signal, and data from orbiting satellites are routinely available [*Shuman and Alley*, 1993; *Shuman et al.*, 1993; *Shuman et al.*, this issue].

Briefly, the thermal radiation upwelling from the snow is monitored at wavelengths of the order of a centimeter and in two polarizations by satellite sensors (most recently the special sensor microwave/imager or SSM/I). Following a snow-

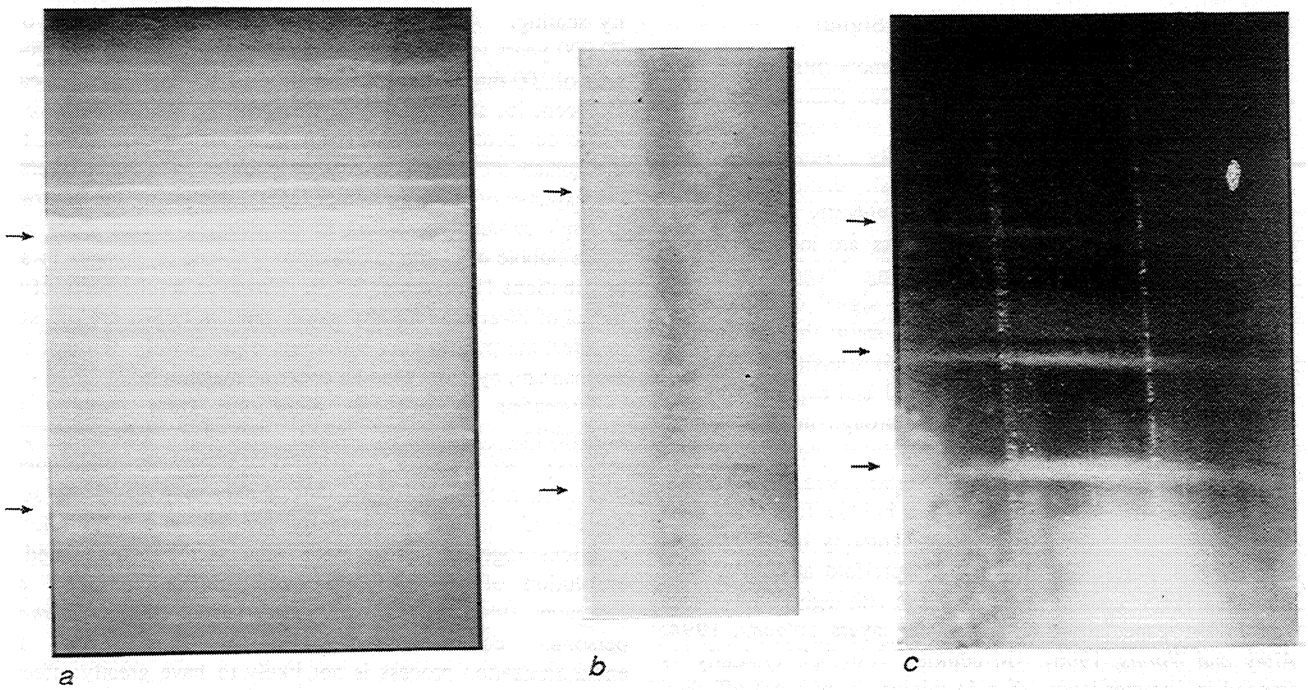


**Figure 1.** Examples of visible stratigraphy, showing (a) annual depth-hoar layers in a snow pit (≈ 60 cm/yr), (b) annual depth-hoar layers in an ice core from 1412 m depth (8.4 kyr B.P., ≈ 10 cm/yr), and (c) annual dust layers in ice from about 1703 m depth (12.5 kyr B.P., ≈ 2.5 cm/yr, Figure 1c). Arrows indicate summertime hoar complexes (Figures 1a and 1b) or springtime dust layers (Figure 1c). In Figure 1a, weak vertical lines or marks were created by the shovel used to excavate the pit. The deeper summer is less clear than the shallower both because of reduced contrast associated with snow metamorphism and because of the difficulty of introducing bright light to the bottom of the 2-m-deep snow pit behind the wall shown that illuminates it. In Figure 1b, the dark band running along the center of the core (the long axis of the picture) is a "window" cut on the back of the core section. In Figure 1c, the bright region near the bottom of the core section is overexposure resulting from a fiber-optic light source placed just out of the picture; the two white bands running along the core length (the long axis of the picture) and parallel, fainter bands are scratches on the upper surface of the core caused by microtoming and then running the electrodes of the electrical conductivity measurement (ECM) probe used at GISP2 (ECM) [*Taylor et al.*, 1992] along the core section.

fall, the snow surface is smooth and provides a sharp density contrast between snow and air at the scale of a centimeter. This means that the snow surface is a specular reflector for upwelling microwaves. Because all reflections are polarized, the satellite sensor records a large difference in intensity of microwaves of different polarization.

The process of depth-hoar formation typically reduces the surface density, creating a density gradient between firn and air over of the order of 1 cm rather than a sharp contrast. Surface-hoar growth extends this gradient and produces abundant roughness at the 1-cm wavelength (see Figure 5 of *Shuman et al.*, [1993]). The result is that the surface no longer acts as a specular reflector at the wavelengths of interest and the difference in intensity between the observed polarizations decreases markedly. (The firn is layered throughout the microwave skin depth of order 1 m, and reflections off those internal layers prevent the polarization difference from dropping to zero. When the upper surface is smooth and hard, it represents the main discontinuity, so progressive changes in it produce a large and characteristic signal; other possible changes in snow properties lack this large, progressive, and characteristic signal.)

During hoar formation, strong correlations exist between surface observations and microwave polarization differences. Furthermore, the calibrated microwave signature from the GISP2 site typically is repeated across the majority of the dry-firn facies of central Greenland at the same time [*Shuman et al.*, this issue]. We thus argue that the processes of hoar formation observed today at the GISP2 site are widespread rather than local phenomena. The relatively small climatic changes observed through the Holocene [e.g., *Grootes et al.*, 1993, *Dansgaard et al.*, 1993, *Meese et al.*, 1994; *Stuiver et al.*, 1995] would not be expected to change greatly the hoar-formation processes or the appearance and other physical properties of the hoar produced.

Sharp reductions in the microwave-polarization difference associated with hoar-forming events are most common between late June and early August. Weaker events occur beyond these times, especially into late August and less frequently into September. One to several events occur per summer [*Shuman and Alley*, 1993; *Shuman et al.*, 1993; *Shuman et al.*, this issue].

Most of our observations are consistent with those of *Benson* [1962]. However, we do not consistently find a clean, well-marked termination of the hoar-forming time such as Benson observed in some areas of Greenland. We thus do not follow *Benson* [1962] in choosing the upper boundary of the hoar complexes as the end of summer; rather, we choose the centers of the hoar complexes as the middles of summers (typically July).

### 2.3 Metamorphism of the Hoar Signal

The annual-layer signal observed in snow pits and shallow cores arises from the contrast between fine-grained, high-density, homogeneous winter accumulation and more variable but typically coarse-grained, low-density summer strata. However, with increasing depth, the density contrast is reduced and then essentially eliminated. Individually recognizable snow grains connected by narrow necks are metamorphosed into continuous, solid ice containing nearly spherical bubbles, causing changes in the visible signal of depth hoar. Empirical tests explained in section 5 show that the annual signal remains recognizable through this transition; here, we discuss the physical processes involved and explain why the annual depth-hoar signal is preserved through much metamorphism.

*Gow* [1968a] and *Gow and Williamson* [1975] showed that at pore close-off, approximately one bubble forms for each grain in a sample owing to the basic geometry of the system. Grain size at pore close-off varies severalfold at GISP2, with summer layers coarser than winter although with much variability, especially in the summer layers [*Woods*, 1994; *Alley and Woods*, 1996]. In addition, more air typically is trapped in summer layers than in winter (pore close-off density is slightly lower in summer layers than in winter layers; [*Martinerie et al.*, 1992; *Schwander et al.*, 1993]). The grain size variations, and to a lesser extent the air-volume variations, cause summer layers below pore close-off (roughly 70-m depth and 200 years age at GISP2) typically to have fewer, larger bubbles but more variability than adjacent winter layers.

Several factors act to affect bubble distributions and the visible appearance of annual layers below pore close-off. As discussed next, however, these processes are not rapid enough to have significantly altered the depth-hoar signal in GISP2 Holocene ice.

The grain growth rate is influenced by impurity loadings and other factors. Above pore close-off at GISP2, grain growth is not sufficient to greatly affect the correlation between coarse grains and summer layers [*Woods*, 1994; *Alley and Woods*, 1996]; thus near-surface conditions control not only the near-surface grain size contrast between layers but also the contrast in bubble size between layers that is produced at pore close-off. With increasing depth and age below pore close-off, differential grain growth increasingly obscures the correlation between summer layers and coarse grains [*Woods*, 1994; *Alley and Woods*, 1996]. However, the interaction between bubbles and migrating grain boundaries is sufficiently weak that it does not seriously alter the bubble distributions during this further grain growth [*Gow*, 1968a; *Gow and Williamson*, 1975; *Alley et al.*, 1986].

Diffusion of air through the ice lattice, combined with the effect of bubble or clathrate surface curvature on equilibrium gas concentration adjacent to bubbles or clathrates, will cause large inclusions to grow while small ones shrink and disappear [*Uchida et al.*, 1994a]. At Vostok Station, Antarctica, roughly 1/3 of the clathrate inclusions were lost to such diffusional coarsening over approximately 70,000 years. This indicates a typical diffusion distance in that time of roughly one inclusion spacing, or roughly 1 mm [*Uchida et al.*, 1994a]. Diffusion rates might be an order of magnitude faster at GISP2 owing to the higher temperature and assuming a plausible activation energy for diffusion, which would increase the typical diffusion distance threefold using the usual square-root-of-diffusivity scaling. A diffusion distance of a few millimeters over 70,000 years is very short compared to an annual layer thickness of 100 mm and a diffusion time of 10,000 years for early Holocene ice at GISP2; hence this process should not have affected our depth-hoar observations significantly. Also, this mechanism would tend to coarsen bubbles in summer layers at the expense of those in winter layers, enhancing the contrast.

High cumulative strains in ice deep in an ice sheet may cause bubble or clathrate collisions and lead to changes in size distributions [*Weertman*, 1968]. However, on the basis of the model of *Weertman* [1968], strain rates at GISP2 are too slow to affect the bubble concentrations significantly through this mechanism, by more than an order of magnitude.

Formation of clathrate inclusions from bubbles and reformation of bubbles from clathrates following core recovery are complex nucleation-and-growth phenomena. When taken to completion, they appear to produce the same number of bubbles as originally present, at similar relative locations, together perhaps with some microbubbles related to exsolution of dissolved gas during relaxation [*Shoji and Langway*, 1983; 1987; *Uchida et al.*, 1994a; 1994b; *H. Shoji*, personal communication, 1996]. Thus even the enclathratization process is not likely to have greatly affected the bubble populations in Holocene ice that has relaxed sufficiently to allow clathrate dissociation.

The possible effects of high ice-age dust concentrations on clathrate formation, coarsening, and dissociation are not well known. When combined with the greater age and cumulative strain of Wisconsinan and older ice, we must entertain the possibility that the bubble distribution, hence the visible-stratigraphic signature of hoar complexes, has been changed by metamorphic processes. However, metamorphic processes are calculated to be insufficient to interfere significantly with the visible identification of Holocene summertime layers. Because this also is entirely consistent with our experience (see section 5.3), we feel confident in Holocene layer counting. We note, however, that detailed bubble studies have not been completed on the GISP2 core and that more useful results are possible.

## 3. Practice of Visible Stratigraphy

Successful visible stratigraphy requires a certain amount of trial and error. If one starts from the assumption that a visible signal is present in the core, then it is necessary to try different surface preparations and lighting until the strata are evident.

For surface preparation, the as-drilled surface seldom is suitable for stratigraphic analysis (although were alcohol or some similar fluid used to fill the borehole, it would smooth the surface and greatly enhance visible stratigraphy [*Gow et al.*, 1968]). Cutting a longitudinal flat surface is thus the first step in stratigraphy. Because continuous sampling of many paleoclimatic indicators requires this type of full-length, sidewall cut, visual stratigraphy can be conveniently performed immediately after such sampling. If the as-drilled surface is especially rough, it may prove helpful to cut a small "window" on the opposite side of the core, giving two smooth surfaces parallel to one another and increasing light transmission.

Even a surface cut by band saw may prove too rough for best observations. Two options for dealing with this include: 1) microtoming the surface after sawing; or 2) polishing the surface by wiping it with an alcohol-dampened cloth. Both improve the cut surface for viewing, although the effect usually is lost within minutes to hours owing to sublimation and other processes.

Illuminating the now-exposed surface is critical. The core should be held in trays with transparent bases and sides, to the greatest degree possible, so that light can be passed through the core from various directions. We started by using a system designed by the GISP2 Science Management Office. Fluorescent tubes were placed below a roller system on which plexiglass-based trays conveyed the core. A translucent light diffuser just above the fluorescent tubes insured uniform lighting. Lights should extend the full length of the core to allow for best viewing. At times, and especially for looking at cloudy bands in Wisconsinan ice, we found that a movable, focused fiber-optic light source with two flexible light guides was especially useful and that changing the angle and direction of illumination helped reveal features. Shining the light in from the end of the core often provided the best view of layers near the ends. Occasionally, the yellowish light of a flashlight proved useful in identifying layers. We experimented a little with filters, such as large, transparent plastic sheets of some color. These seem to help in places, but we did not find them sufficiently useful for routine application. Shadowing, the casting of a shadow using a board or similar item and then moving the shadow along the core, made it easier to detect some features and was especially useful in observing cloudy bands in ice from deeper than 2000 m.

For all such work, extraneous light reflecting off the cut surface of the core complicates the observations. Some sort of shielding over the core and the observer is required for best results (a sort of "dark-room").

We found that it is easiest for an observer to start in snow pits, where the annual signal is strongest, and then follow the signal continuously through the gradual diagenetic and metamorphic changes with increasing age and depth. However, with a little effort, it is possible for an observer to start somewhere along the core and still produce accurate results. Overlapping of observers facilitates this.

We attempted to image the core, using still photography and video recording. Neither technique, in our implementation, proved routinely capable of recording on a continuous basis the subtle features that formed the basis of our stratigraphy. The simple fact that we required such techniques as changing light color, intensity, and direction indicates that a single-mode recording system will have difficulty. We hope that improved, computer-based imagery followed by image enhancement will allow better recording. Figure 1b shows one of our best examples of an annual signal in ice, yet the signal appears subtle in this photograph taken to highlight the contrast.

For our project, the main record is a series of core log books. These books, each containing approximately 50 sheets of 1 m long by 10 cm graph paper, were marked with all significant features observed, providing a 1:1 "map" of the entire core. We typically marked breaks in the core, visible features such as bubble-free layers, layers that were unusually dark or bright in transmitted light, prominent relief at layer interfaces, or light transmissivity varying rapidly between adjacent structures. We then interpreted these features on the core logs, such as melt layers, summer layers, etc. These interpretations were "digitized" by typing the depths and some identifying code into a computer. Care must be used to avoid errors in this tedious digitization process, as noted below.

The indications of annual layering are often rather faint. It usually proved useful to inspect an entire meter of core, identifying the major features and their relation to each other, before recording the observations on the log. Working with 2-m-long core sections is even easier than with 1-m-long sections, as it reduces the uncertainty in placement of summers and other features when they continue from one core section to the next.

## 4. Coverage and Timeline

Visible observations of the entire core were made in the field at the GISP2 site. Because core recovery stretched over several months per summer for five summers, multiple observers were active. Main observations were taken by R.B. Alley and C.A. Shuman of the Pennsylvania State University, and A.J. Gow and D.A. Meese from the Cold Regions Research and Engineering Laboratory. Significant guidance was provided by K.M. Cuffey, then of the Pennsylvania State University, and also by P.M. Grootes, then of the University of Washington; many other workers contributed their opinions at times. Table 1 lists the field chronology of observation. Tables 2 and 3 reveal some of the redundancy provided by multiple counting including much work at the National Ice Core Laboratory, Denver, Colorado, USA; additional counting data are presented by *Meese et al.*, [this issue].

## 5. Accuracy

### 5.1. Holocene

Errors are associated with core or data loss, with uncertainty in counting of layers, and with any imperfection in the way the ice sheet recorded annual signals. Looking first at data loss, some core sections were not of sufficiently high quality to be analyzed in the regular core-processing line, which included our visible stratigraphy. This data loss, which occurred primarily in the brittle-ice zone (see below) and totaled 87 m, is indicated in Figure 2. The lengths of core sections involved usually are known accurately, because the core was recovered but wafered or splintered in the core barrel so that it could not be clamped, sawed, and examined efficiently. For the regions of data loss, which varied from centimeters to meters in length, we interpolated layer thicknesses based on annual layers observed above and below.

Such interpolation must have some associated error. The standard deviation of annual accumulation in well-sampled Holocene sections spanning a few decades is roughly 15% of the mean [*Bolzan and Strobel*, 1994; our work]. Assuming uncorrelated errors, the variability associated with interpolations across the roughly 500 years in the 87 m of visible data loss should be substantially less than 15% owing to the usual reduction in error associated with large samples. If we rather arbitrarily choose 10% as a conservative estimate for the interpolation error, then this data loss affects the cumulative ages through the Holocene by zero at the surface (the core is well tied to the surface) increasing to roughly 50 years below the deepest data loss.

We turn next to the errors associated with layer counting. The original test of the visible layer counting was conducted

**Table 1.** Field Chronology of Visible Observations for Dating

| Year | Observer | Depths, m |
|---|---|---|
| 1989 | Alley<br>B core | 0-200 |
| 1990 early | Alley<br>with Cuffey | 100-130 |
| 1990 late | Gow<br>with Meese | 130-335 |
| 1991 early | Alley<br>with Cuffey | 335-679 |
| 1991 late | Meese | 679-719<br>1371-1510 |
| 1992 early | Alley | 719-1371<br>1510-1523<br>some deeper |
| 1992 late | Shuman | 1517-1867<br>some 1867-2250 |
| 1993 | Gow | 2250-2810 |

The B core was collected in 1989 and the D core in 1990-1993. The GISP2 climate record is a composite of the upper parts of the B core (to roughly 150 m) and the D core below that. Notice that because of storage of the brittle ice to allow relaxation and other factors, the core was not always analyzed consecutively.

by one of us (R.B. Alley) in the field during 1989 and consisted of counting visible layers down the core to the depth of the fallout of debris from the 1783 eruption of the Icelandic volcano Laki, as identified by electrical conductivity of the ice [*Taylor et al.*, 1992]. For this purpose, a tally of years counted was kept on a slip of paper next to the official core logs. Initially, this count differed from the expected age by 5 years, or 2.5%. Subsequent study of the official logs showed that 3 years recorded in the log book had not been transferred to the tally sheet, such that the error was 2 years or 1%. The argument of *Fiacco et al.*, [1994] that the layer detected electrically was deposited on Greenland in 1784 rather than 1783, using the temporal relation between tephra deposition and volcanic-aerosol deposition, would reduce the error to 1 year or 0.5%. The count down to the volcanic fallout from Tarumai, in 1667, missed 1 additional year, for an accuracy just better than 1%.

**Table 2.** Repeatability of Holocene Visible-Stratigraphic Counts, GISP2 core

| Depth, m | Count 1 | Count 2 | Diff. |
|---|---|---|---|
| 159-345.6 | 3G 1990=817* | A 1993=825 | +1% |
| 335-346 | A 1991=50 | A 1993=49 | 2% |
| 335.2-679.0 | 3A 1991=1768* | A 1991=1765 | -0.2% |
| 679.3-711.2 | 3M 1991=189* | A 1993=190 | +0.5% |
| 1371-1510 | 3M 1991=1355* | A 1993=1427 | +5.2% |
| 1513-1668 | S 1992=2074* | A 1993=2050 | -1.2% |
| Totals | 6203* | A=6257 | +0.9% |

The visible observations were made by Alley (A), Gow (G), Meese (M), or Shuman (S) during the year indicated. In some cases, they were refined in the dating committee effort (D. Meese, chair) using electrical conductivity, some laser-dust records, and some isotopic data, typically for a total of three parameters, indicated as 3A, 3G, or 3M depending on who did the visible stratigraphy.

*"Official" counts from the GISP2 Dating Committee, such as used by *Mayewski et al.*, [1993] [see Meese et al., this issue]. The percentage difference of the second count from this official count is indicated as "Diff."

**Table 3.** Repeatability of Wisconsinan Visible-Stratigraphic Counts, GISP2 Core, for Selected Sections of Core Between the Depths Indicated

| Depth,.m | Count 1 | Count 2 | Diff. |
|---|---|---|---|
| 1678-2250 | S=444 | A=442 | 0.5% |
| 1678-2250 | S=268 | M=233 | 14.0% |
| 1678-2250 | A=493 | M=504 | 2.2% |
| 2250-2692 | A=1178 | M=1163 | 1.3% |
| 2250-2692 | A=1178 | G=1275 | 7.9% |
| 2250-2692 | M=1163 | G=1275 | 9.2% |
| 1678-2250 | S=401 | X=421 | 4.9% |
| 1678-2250 | A=608 | X=544 | 11.1% |
| 1678-2250 | M=416 | X=342 | 19.5% |

The number of years counted by Alley (A), Gow (G), Meese (M), or Shuman (S) is indicated. Overlapping counting is not continuous within the depth ranges indicated, and not all observers studied all sections for which at least two observers overlap. Also indicated are some results of lagged autocorrelation applied to laser-light scattering data from *Ram and Illing* [1994] using the xvgr graphics and statistical package (X). The depth ranges chosen are 1678 m = 11.65 kyr B.P., end of the Younger Dryas; 2250 m = 39.85 kyr B.P., end of one drilling season and switch of visible-layer stratigrapher in the field; and 2691 m = 87 kyr B.P. based on the *Bender et al.*, [1994] correlation to SPECMAP, the deepest level at which we have counts by three visible-layer stratigraphers. Significant differences appear between the Bender et al., correlation to SPECMAP and the cumulative layer count in the vicinity of 2430 m or 50 kyr B.P. Also see *Meese et al.*, (this issue) for comparisons in deep ice. "Diff." is the absolute value of the difference between the two counts, divided by their mean and expressed as a percentage.

This exercise emphasized the difficulties associated with digitization of a paper record which now, including duplication, is well over 3 km long. It also convinced us that the visible stratigraphy was functioning accurately. The initial field work was not performed under ideal conditions. Core quality was variable and occasionally quite poor. We also had not fully mastered some of the lighting and surface-polishing techniques that later proved to be so valuable. We thus do not believe that this level of accuracy is unusual or unnatural but that it is a typical level of achievement.

Dating of the GISP2 core then proceeded through a series of refinements. We first worked on intercomparisons of the electrical conductivity method or ECM [*Taylor et al.*, 1992], high-resolution (10 samples/yr) oxygen isotopes [*Grootes et al.*, 1993] (Figure 3a), and visible strata [*Alley et al.*, 1990]. These three records agreed in almost all cases. Occasionally, there would be offsets between annual-layer picks from these records or even a "drift" in which mismatches of a significant fraction of a year occurred between summer picks for one to a

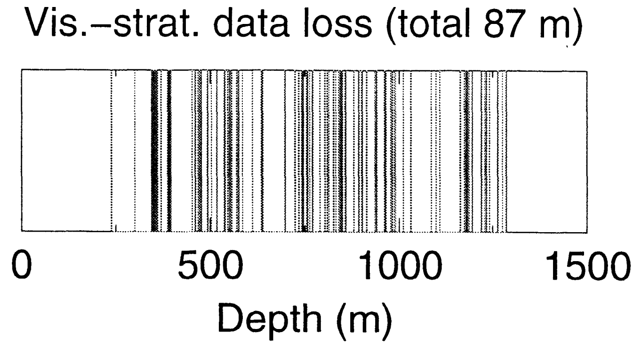


**Figure 2.** Regions of visible-stratigraphic data loss owing to poor core quality, totaling 87 m. Note that data loss appears somewhat worse in the figure than in reality because the lines used in plotting are sometimes thicker than the actual data loss.

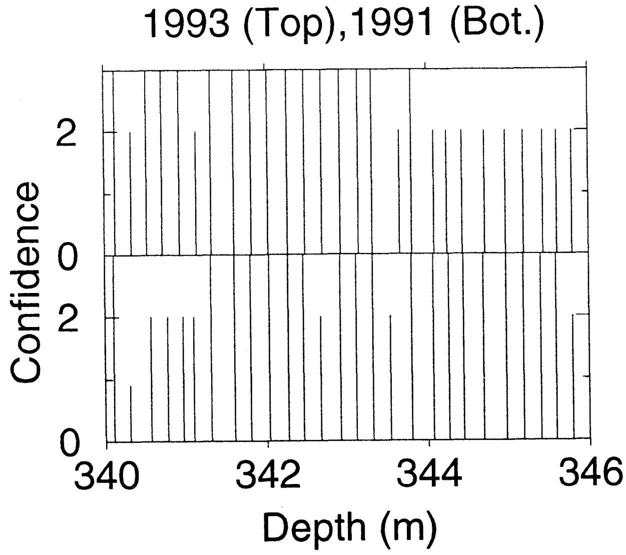


**Fig 3b**. Comparison of visible stratigraphy conducted by R.B.A. (top) independently at the National Ice Core Lab (NICL) in 1993 and (bottom) in the field in 1991. Locations of summer picks are shown by vertical bars, with the length of the bar indicating how confidently the summer was picked. Both counts obtained 27 summers in this interval.

few years before coming back together. An example of an intercomparison is given in *Taylor et al.*, [1992], and others are shown by *Taylor et al.*, [this issue] and *Meese et al.*, [this issue]; also see Figures 3a-3g for several examples. At all times, we were aware of time markers provided by volcanic eruptions and other events dated historically or in many other ice cores [e.g., *Hammer et al.*, 1978; *Clausen et al.*, 1988].

In 1991, the dating was centralized under a dating committee with D.A. Meese as the chair. Dating was expanded to include a variety of other annual indicators and especially laser-light scattering from dust [*Ram and Illing*, 1994], where available. Deeper ice was dated by correlation of the GISP2 data into the marine realm through the isotopic composition of oxygen in air bubbles [*Bender et al.*, 1994]; correlation of tephra from single volcanic events with marine cores and with the GRIP core [*Zielinski et al.*, this issue; *Grönvold et al.*, 1995], and correlations into the marine realm through climate-record curve-matching [*Bond et al.*, 1993; *Bond and Lotti*, 1995], also contribute.

Visible strata remained the major indicator for most of the core, however. Strengths of visible stratigraphy included the

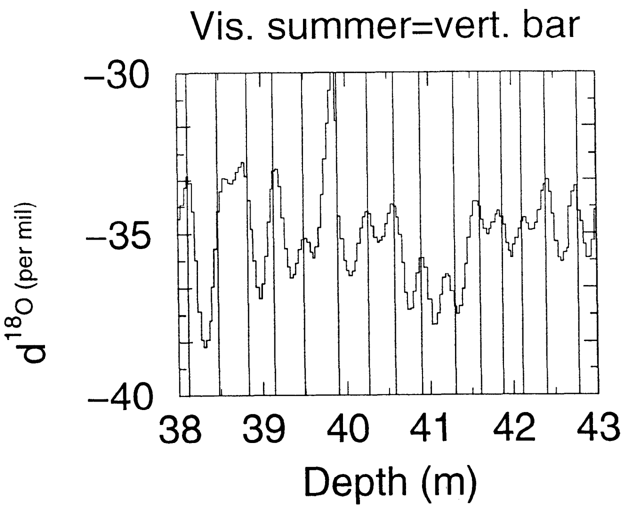


**Figure 3a.** High-resolution oxygen-isotopic ratios [*Grootes et al.*, 1993] showing annual cycle, and summer picks from visible stratigraphy (R.B.A.) shown as vertical lines. For these 5 m, the agreement is excellent. For similar plots, see *Taylor et al.*, [1992], and *Taylor et al.*, [this issue]. Isotopic measurements were made on samples cut from along the core and then subsectioned; visible observations were made on remaining core. Every effort was made to maintain registry, but some offset between isotopic and visible summers may arise from registration problems as well as from true variability.

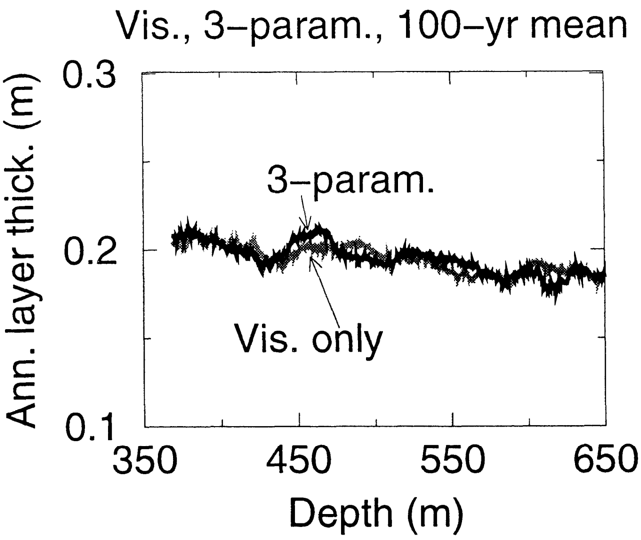


**Figure 3c.** Annual layer thicknesses, smoothed with 100-year running mean, for approximately 300 m (1200 years). Visible stratigraphy was conducted in the field by R.B.A. and then modified by D.M. and A.J.G. in light of ECM and laser-light-scattering data. The general downward trend with increasing age abd depth is related to strain in the ice sheet; the variations from that trend are caused by accumulation-rate variations, and the agreement between the two lines shows how well the visible data and the modified data agree on those accumulation-rate variations. The cumulative difference in total years is 0.2% over this period.

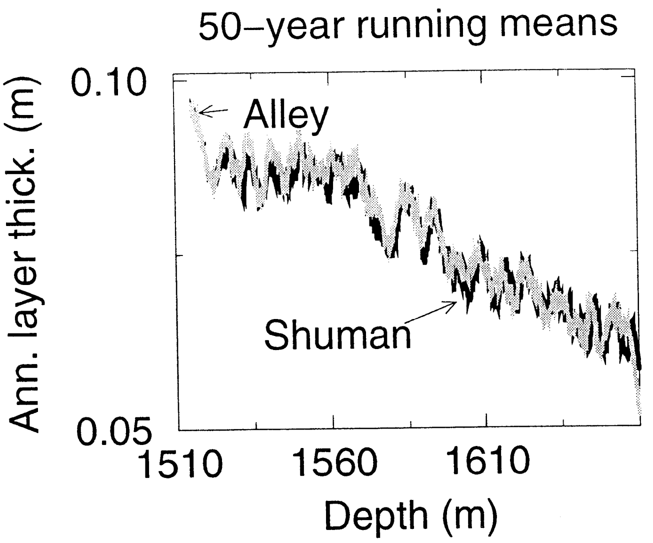


**Figure 3d.** Annual layer thicknesses, smoothed with 50-year running mean, for approximately 150 m (2000 years). Visible stratigraphy was conducted in the field by C.A.S. in 1992 with observations mainly of dust layers and at NICL by R.B.A. in 1993 with observations mainly of depth hoar after clathrate dissociation returned bubbles that obscured cloudy bands. The general downward trend with increasing age and depth is related to strain in the ice sheet; the variations from that trend are caused by accumulation-rate variations, and the agreement between the two lines shows how well the visible data and the modified data agree on those accumulation-rate variations. The cumulative difference in total years is 1.2% over this period.

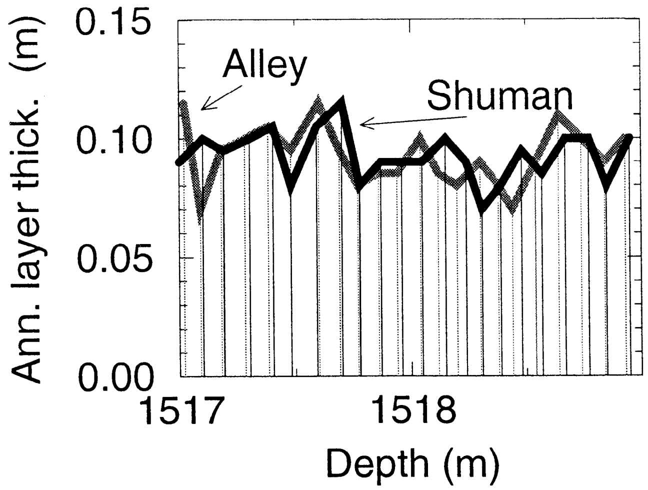


**Figure 3e.** Close-up of a section of Figure 3d. A slight offset is evident between most of the Alley and Shuman picks, reflecting the typical difference in position between the springtime dust peak and the summertime depth-hoar peak. For this section, we picked exactly the same years, but annual accumulations differ owing to spring-spring versus summer-summer differences and possibly owing to human factors. The annual-layer thickness is plotted at each summer and represents the distance to the next shallower summer pick.

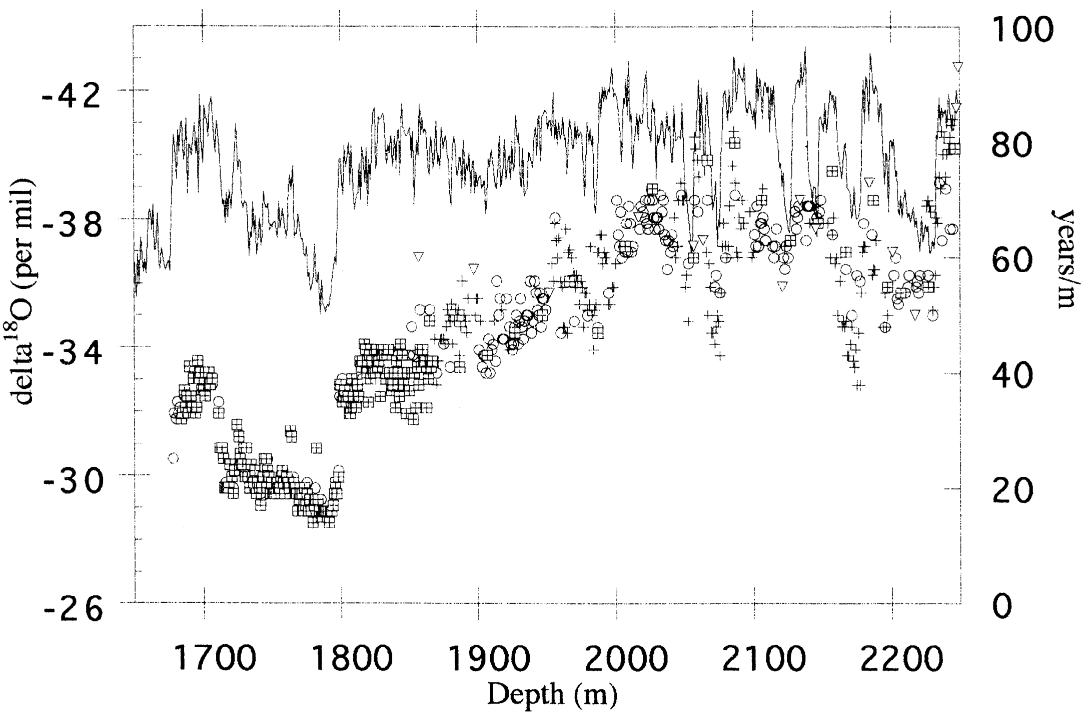


**Figure 3f.** Repeatability of visible stratigraphy in the late glacial. Shown are counts in layers per meter by four visible stratigraphers, together with the oxygen-isotopic curve from Grootes et al., [1993] in per mil, multiplied by -1 to make display easier. The general upward trend in years per meter with increasing depth is caused by strain in the ice sheet. Parallel variability is evident for the isotopes, a proxy for temperature, and the years/meter, a proxy for accumulation (also see *Stuiver et al.*, [1995]). Agreement among the four stratigraphers [Alley, Gow, Meese, and Shuman] can be assessed from the positions of the different symbols and roughly is the width of the band of symbols; also see Table 3.

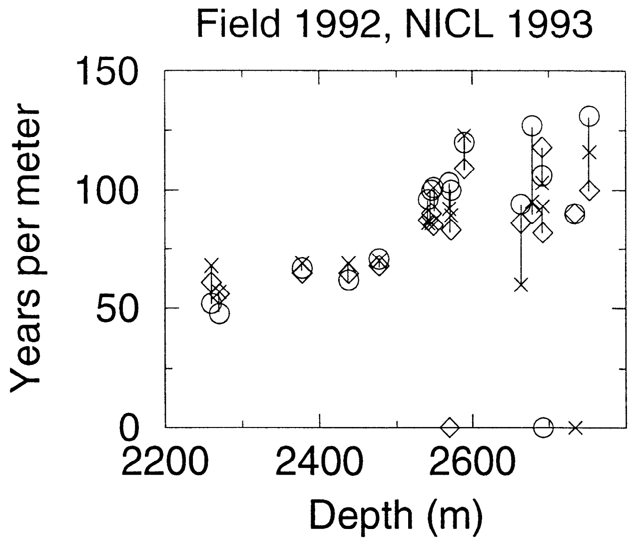


**Figure 3g.** Repeatability of visible stratigraphy in deeper sections of the core. Layer counts appear accurate to about 2450 m (51 kyr B.P.). As shown here, different observers in the field and at the National Ice Core Laboratory (NICL) obtained similar counts shallower than that but obtained larger differences deeper. Shown are number of years per meter for each counter at a depth, connected by a short line segment. Zero is indicated if an individual did not study that meter.

almost immediate production of a timescale that subsequently did not require significant adjustment through the Holocene and on to roughly 50 kyr B.P. (see below), as well as its clear linkage to insolation and thus to the calendar seasons through the Holocene. Also, visible strata remained evident in all of the brittle ice we processed, but the abundant breaks made interpretation of electrical or laser-dust records more difficult. (Typically, firn and shallow ice are easy to work with, but increasing bubble pressure with increasing depth causes the ice to become "brittle" and prone to easy or spontaneous fracture. Core from this brittle-ice section usually contains numerous breaks by the time analysis is completed. Still deeper, the air from the bubbles forms a clathrate solid phase with the ice, and the brittleness is lost [see *Gow et al.*, this issue].)

We believe that a multiparameter approach is the best way to date an ice core. However, in the multiparameter dating as in single-parameter dating, we were faced with problems such as the short regions of data loss that complicated the dating process. Failure of visible stratigraphy to match an historical volcano to the exact year might arise from error in visible stratigraphy, which we expect, but it also might arise from error in interpolating across a region of data loss. The possibility of error in dating a volcanic eruption or in assessing the time between a well-dated eruption and fallout on the ice sheet [e.g., *Robock and Free*, 1995; *Baillie*, 1996] must also be considered. When the dating committee adjusted the initial visible stratigraphy using other indicators but without regard to timing of volcanic fallout, perfect matches still were not obtained in all cases when comparisons were then made to volcanic indicators, and often the match was no better than for visible stratigraphy alone. We believe that this indicates errors from sources other than layer counting rather than inherent imperfection in the ice-core record or in the multiparameter approach, although we cannot prove this. Again, the errors were at the 1% level over 100-year time periods, certainly not large, but not zero.

Reproducibility of the Holocene visible layer counting is detailed in Table 2 and Figures 3a-3g. Counts were made in the field and then repeated at the U.S. National Ice Core Laboratory in Denver during subsequent years. Intercomparisons are listed between two visible stratigraphers, between one visible stratigrapher at different times (Figure 3b), and between visible stratigraphy alone and visible stratigraphy adjusted using other indicators including oxygen isotopic ratios, electrical conductivity, and laser-light scattering from dust (Figure 3c). For the most recent 2 millennia, down to 79 A.D. (the Vesuvius eruption, probably the oldest large eruption historically dated to the year), multiparameter (typically three) dating was conducted to match as closely as possible all available annual indicators and the known volcanic markers. Deeper, no such tuning was used primarily because the error in the radiometric dating of the older eruptions may very well exceed our counting error.

Most of the intercomparisons are at the 1% level (Table 2). That from 1371 to 1510 m is somewhat worse and is of some concern. We cannot fully explain this discrepancy. We note that visible stratigraphy conducted in the field in this section was probably relatively more difficult, because clathrate formation had removed most of the bubbles, but the ice was not dusty enough to allow consistent identification of cloudy bands by inspection, at least in the presence of the remaining bubbles. Thus the multiparameter dating in this section has a weaker underpinning of visible strata than for other sections of the core. When the stratigraphy was repeated 2 years later, clathrate dissociation had caused bubbles to be more visible, and routine visible stratigraphy was possible. Laser-light scattering [*Ram and Illing*, 1994] across this region did detect annual dust fluctuations, but this measurement was not completed in the field.

### 5.2. Time Marker: the End of the Younger Dryas

Below the depth of historically dated volcanoes, other ways must be sought to confirm the accuracy of the annual layer counting. Intercomparison to the Greenland Ice Core Project (GRIP) dating and to other Greenland ice-core dates based on layer counting [*Johnsen et al.*, 1992] provides evidence of matches at the 1% level for prominent Holocene events; the consistency is encouraging. This is further shown by the absolute match between tephra in the GISP2 and GRIP cores [*Zielinski et al.*, this issue].

The most notable marker is the termination of the Younger Dryas cold event, which many would take as the onset of the Holocene. We have joined most other workers in assuming that this is a near-synchronous event wherever it is well recorded. In Table II of *Alley et al.*, [1993] we listed several independent ages for the termination of the Younger Dryas, and argued that our estimate (11,640 ± 250 years B.P.) was consistent with most other available published estimates for the termination at around 11,500 ± 200 years B.P. (The *Alley et al.*, [1993] error estimate included uncertainty from counting and interpolation, and was believed to be "slightly conservative".)

Since then, a few new results have been published. By using U-Th to calibrate radiocarbon dates, *Edwards et al.*, [1993] obtained a range of 11,000-12,500 for the end of the Younger Dryas. Through a combination of tree-ring-calibrated radiocarbon and varve chronologies, *Hajdas-Skowronek* [1993] dated the termination of the Younger Dryas in Soppensee, Switzerland, to 10,986 ± 69 years B.P., but *Hajdas et al.*, [1995] obtained 11,490 years B.P. for the termination in Lake Holzmaar, Germany using similar techniques. Again using similar techniques, a varved sequence from Lake Gosciaz, Poland yielded 11,440 ± 120 years B.P. for the Younger Dryas termination [*Goslar et al.*, 1995].

There appear to be no obvious problems with the Soppensee date, but it in turn is clearly not in agreement with those from Holzmaar and Gosciaz. We thus remain concerned, but we retain our original interpretation of 11,500 ± 200 years B.P. as being the most likely age for the end of the Younger Dryas, based on available evidence. Taking this assumption, we then note that the ice-core layer counting is entirely consistent. Our age of 11,640 ± 250 years B.P. [*Alley et al.*, 1993] has not been changed during further analyses [*Meese et al.*, this issue], and we do not anticipate any significant changes.

In section 6, below, we discuss a visible-only time scale, prepared for consistency rather than for maximum accuracy. That timescale includes an estimate of confidence for each summer pick. High confidence indicates that the signal was very clear; low confidence indicates that we were unsure of a pick for some reason, either because of low signal quality, low core quality, or some other factor. If we count every year in this visible-only time series, we obtain 11,690 years B.P. for the end of the Younger Dryas.

We also tried various methods of estimating layer thicknesses between summers picked with high confidence and then interpolating across those regions where confidence was lower [*Spinelli*, 1996]. This depends somewhat on the window size and cutoff confidence used for interpolation. A variety of tests typically yielded a slightly younger age for the termination of the Younger Dryas, in the neighborhood of 11,520 years B.P. That difference of 170 years may represent any number of things, but is another estimate of the potential variability inherent in the visible-layer counting. Our data continue to be consistent with most other estimates for the age of the end of the Younger Dryas, which in turn suggests that the layer counting is as accurate as the independent techniques available to date this transition.

### 5.3 Intercomparison with Dust: Early Holocene

One of the main indicators in multi-parameter dating is laser-light scattering from dust in the ice core [*Ram and Koenig*, this issue; *Meese et al.*, this issue]. Scattering was conducted on meltwater and on solid ice, revealing clear annual signals [*Ram and Illing*, 1994; *Ram et al.*, 1995; *Ram and Koenig*, this issue]. Dust also influences the ECM signal [*Taylor et al.*, 1992]. In addition, the early part of the Holocene and most of the older ice contain "cloudy bands" [cf. *Kipfstuhl and Thorsteinsson*, 1993], which seem to correlate well in position with highs in laser-light scattering and lows in electrical conductivity and thus with those regions where we infer high dust concentrations. For the early part of the Holocene, our initial dating relied on visual identification of cloudy bands in the core. This began in regions where a few bubbles were visible, and some calibration was possible between the two indicators. Subsequently, bubble growth following clathrate dissociation has caused a stronger depth-hoar signal to appear in this ice, allowing further calibration. Excellent agreement was obtained (see below), with the dust peak typically preceding the summertime depth-hoar complex by a small fraction of a year, indicating peak dust concentration in springtime.

For the Younger Dryas and older ice, our observations in the field and during subsequent examinations of the core have relied on cloudy bands; although the bubbles are returning, changes are ongoing and we are not yet confident that they have reproduced a true depth-hoar signal. The high levels of dustiness in Wisconsinan ice would be more likely to affect the nucleation and growth of bubbles from clathrates than the low Holocene levels. For the early Holocene, the signal that returned was so like that from shallower ice lacking clathrates that we are confident of it (also see section 2.3).

The easiest calibration check between the cloudy bands/dust layers and the depth-hoar layers is that from 1513- to 1668-m depth, comparing the field counts of C.A. Shuman (C.A.S.), based primarily on dust, to the laboratory counts of R.B. Alley (R.B.A.), based primarily on depth-hoar indications (Figures 3d and 3e). The net difference is 1.2% over 2000 years. These comparisons were done in two ways. For about 15% of the record, R.B.A. counted the depth-hoar layers and then compared them to the cloudy-band counts of C.A.S. For the rest of the record, R.B.A. placed the cloudy-band logs of C.A.S. against the ice core and then either agreed or disagreed based on inspection of the depth hoars. Interestingly, for those done without looking at the C.A.S. logs, the match was even better: 1.0%.

A different way to look at this calibration is to compare the accumulation-rate time series obtained from the R.B.A. and C.A.S. dating over this interval, corrected for ice flow in the same way following *Alley et al.*, [1993]. Because accumulation rate is derived from the dating, an error in identification of a year creates both an anomalous accumulation year and an offset of all subsequent years between the two time series. Not surprisingly, then, the correlation coefficient between the R.B.A. and C.A.S. raw data is quite low (0.32 at the optimum lag of 21 years between the two data sets; 0.24 for zero lag). Encouragingly, smoothing reveals the great commonality between the two data sets, with the correlation coefficient rising above 0.98 for 100-year running averages.

### 5.4 Pre-Holocene Counting

In dating from cloudy bands, the technique remains to locate repeating patterns and count them. The typical observation is of a springtime dust peak [cf. *Taylor et al.*, 1992] (also see above). Sometimes we observe more than one relatively strong-looking cloudy band per year, and a secondary fall peak is not unusual.

We have tried various ways of counting cloudy bands, including human counting of laser-dust records, human counting of ECM records, Fourier transforms and lagged autocorrelations of these digital records, and visible stratigraphy. Typically, all yield similar results in the late Wisconsinan. With increasing age, first ECM and then, at roughly 50 kyr B.P., visible stratigraphy begin to miss years based on comparison to independent ages (see below) and on intercomparison among indicators.

Visible-stratigraphic reproducibility in the Wisconsinan is not as good as for Holocene depth-hoar layers. Several factors may contribute. The lower average annual accumulation during the Wisconsinan increases the probability of wind scouring and snow drifting disrupting the annual stratigraphy. With increasing depth, one increasingly encounters evidence of flow disturbance of layers [e.g., *Alley et al.*, 1995], which complicates the interpretations. Extreme layer thinning can cause resolution problems. In addition, we speculate that the Wisconsinan dustiness signal truly is "noisier" than for Holocene depth hoar. Although dust delivery to the GISP2 site must be related to the seasonality of dust sources and of weather patterns, occasional "odd" weather patterns or volcanic eruptions could produce dust deposition at the site at almost any time of year. In comparison, because the Sun shines in the summer and not in the winter, the visible-stratigraphic signal is more strongly linked to seasonality [*Alley et al.*, 1990].

In Figures 3a-3g and Tables 2 and 3 we show repeat counts from visible stratigraphy of the ice core. In some cases, the repeat counting was conducted after a 10-cm-long section had been removed for other studies; if so, we counted layers in 90 cm and scaled up to a meter. Wisconsinan counts by C.A.S. are all from shallower than 2250 m, and those by A.J. Gow (A.J.G.) are all from deeper than 2250 m where counting was more difficult. C.A.S. and A.J.G. counted in the field, and others (including further work by A.J.G.) in the National Ice Core Laboratory (NICL) (See Table 1); R.B.A. conducted some late Wisconsinan counts in the field. The field work in the Wisconsinan is probably better than the repeats at NICL, because core quality and cloudy-band visibility were better in the field owing to the effects of bubbles obscuring cloudy bands following clathrate dissociation. Nonetheless, accurate counts were possible in the lab for at least 2-3 years after core recovery. We believe that ongoing work on interpretation of the laser dust and ECM will improve the layer counting, although dramatic improvement is not possible in ice younger than about 50 kyr B.P. because of the high accuracy already achieved.

Agreements between counters are better at shallow depth than at greater depth. The results as a whole are encouraging, suggesting reproducibility of about 5% (the mean of the magnitudes of the differences among the counters, weighted by the number of years involved).

We also show results in Table 3 from lagged autocor-relations on selected sections of the laser-light-scattering record for the core, followed by identification of a prominent peak associated with what we take to be an annual signal. Typically, we used somewhat less than a full meter for this, as full meters often did not produce "clean" autocorrelation peaks. The lagged autocorrelation does not seem to match the various human counters as well as they match each other; we believe the visible stratigraphy more than we do the lagged autocorrelations. We include the lagged autocorrelations in part to illustrate the difficulty of automated processing of the data; although almost any signal-processing technique will detect periodicities in ECM and laser dust if they are sampled with sufficiently high resolution, reliably extracting individual years is not extremely easy.

We have limited ability to check the accuracy of our counts, but it appears that layer-count accuracy and reproducibility are similar. Based on similarity of climate signals, *Bond et al.*, [1993] and *Bond and Lotti* [1995] correlated high-resolution ocean-sediment records of the North Atlantic to ice-core records from the Greenland summit. The cold time immediately following Interstadial 5 [*Dansgaard et al.*, 1993] was correlated with the peak in lithic grains just below Heinrich event 3 in the sediment cores, which is radiocarbon dated to 27.5-28$^{14}$ kyr B.P. Using the U-Th calibration of *Bard et al.*, [1990], which includes a sample of almost exactly that age, this translates to about 30.5 kyr B.P. calibrated years. (The Bard et al., calibration sample yields 27,909 ± 1560$^{14}$C years B.P. versus 30,470 ± 240 years B.P. by U/Th.) The same level, as nearly as we can identify it through the curve-matching, is layer-counted in the GISP2 ice core at 31 kyr B.P. [*Meese et al.*, 1993]. This indicates a cumulative error of less than 2%. This depth, about 2100 m, is in the region where we still obtain excellent reproducibility among visible-layer stratigraphers.

Absolute ages for comparison are scarce below this level. *Bender et al.*, [1994] used the oxygen-isotopic composition of trapped air in the GISP2 core to correlate via the Vostok, Antarctica ice-core record to the SPECMAP (Spectral Mapping) stack for the oceans [*Imbrie et al.*, 1984], which is absolutely dated at certain horizons and then refined through orbital tuning. This indicates that the cumulative visible-stratigraphic layer counts are quite accurate to roughly 50 kyr B.P. At 2450 m, the layer counting yields 51.2 kyr B.P. whereas the gas correlations, corrected for the gas-age/ice-age difference, yield 52.4 kyr B.P., or a cumulative accuracy of roughly 2%, somewhat smaller than the joint uncertainties. Taken at face value, the layer count is now younger than the independent age rather than older, which would indicate an undercount of almost 8% between 30.5 and 52.4 kyr B.P.; however, the uncertainties on both of the independent ages are large enough that there equally could be no counting error at all. At greater depths, however, visible stratigraphy significantly undercounted the number of layers present based on the *Bender et al.*, [1994] correlation to SPECMAP. We remain hopeful that further study using multiple parameters, especially laser-dust measurements [*Ram and Koenig*, this issue; Meese et al., this issue], and with the knowledge provided by the *Bender et al.*, [1994] calibrations, will allow layer counting to be extended even further. Explanations for the discrepancies at times older than 50 kyr B.P. remain speculative.

## 6. Sources of Error in Visible Stratigraphy

In common with all other methods of layer counting, visible stratigraphy has certain weaknesses. Probably the biggest weakness is that the signal is variable along the full core length (sometimes subtle, sometimes obvious); unless the observer is careful and persistent, it is likely that large errors will result. Our experience with asking visitors to look at the core has been that some people identify exactly the same features as the experienced stratigrapher, whereas others will go so far as to assert that nothing whatsoever is visible. Difficulties with poor observational conditions can compound this; rough core surface or numerous breaks are of concern. We note, however, that the brittle ice posed much smaller problems for visible stratigraphy than for other observational techniques, probably because of the great adaptability of visible stratigraphers.

The visible signal is not purely one of seasonal insolation. As discussed by Alley [1988]; (also see *Shuman et al.*, [1995, Figure 1a]), it is possible to have depositional depth-hoar layers form at any time of the year. These typically are thinner and of higher density than the summertime diagenetic depth-hoar layers and so can be distinguished readily in snow pits, but they could complicate observations at greater depths in the core. Similarly, other features occasionally are visible in ice cores (e.g., forest-fire-fallout layers, volcanic dust), which complicate the signal. We have demonstrated that visible strata are strongly seasonally controlled, but we do not believe that they are perfectly seasonally controlled.

Fundamentally, in counting any annual marker, we must ask whether it is absolutely unequivocal, or whether nonannual events could mimic or obscure a year. For the visible strata (and, we believe, for any other annual indicator at accumulation rates representative of central Greenland), it is almost certain that variability exists at the subseasonal or storm level, at the annual level, and for various longer periodicities (2-year, sunspot, etc.). We certainly must entertain the possibility of misidentifying the deposit of a large storm or a snow dune as an entire year or missing a weak indication of a summer and thus picking a 2-year interval as 1 year.

Counting of layers in ice cores is often compared to dendrochronology. When properly used, tree-ring dating produces zero-error ages. Notice, however, that "occasionally trees will produce false rings...in extreme years some trees may not produce an annual growth layer at all, or it may be discontinuous" and "two or three cores should be taken from each tree and at least 20-30 trees should be sampled at an individual site" [*Bradley*, 1985, p. 334-335]. Where similar care has been taken in ice cores with a sufficiently high accumulation rate, zero-error ages also are obtained based on intercomparison and calibration to historical volcanic eruptions [e.g., *Hammer et al.*, 1978; *Mosley-Thompson et al.*, 1993), particularly when the presence of tephra can verify the aerosol signal [*Palais et al.*, 1991].

Perhaps the main practical difference between ice-layer and tree-ring dating is the difficulty of the core recovery and handling in the ice-core case. The GISP2 core, for example, is 3 km long, weighs approximately 40 tons, and required tens of people working over five summers to collect. It is obvious that the ideal tree-ring standard of tens of repetitions to guarantee perfect accuracy is not practicable in the deep-ice-core case, although it is being approached for the most recent centuries [e.g., *Hammer et al.*, 1978; *Clausen et al.*, 1988; *White et al.*, this issue].

We thus must accept that single-core dates, and especially single-core/single-indicator dates, involve some uncertainty. Furthermore, they will involve some "personal" factor, because the way different people deal with the uncertainty in counting years may be different. When faced with a question of whether one is looking at a single long year or two short ones separated by a weak seasonal indicator, some individuals will make one decision and some will make the other ("lumpers" and "splitters"). It is unlikely that such decisions will be random.

We observe this behavior in our intercomparisons. Although we see no statistically significant differences in dating by different visible stratigraphers through the Holocene, we do see small but significant differences in the interannual variability of recorded layer thicknesses between some visible stratigraphers. Careful examination of the data shows that some of the difference in variability is related to placement of the summer maximum within the depth-hoar zones. Because the zones tend to lack sharp, unequivocal onsets and terminations, there is some freedom in choosing the midsummer level, which in turn allows for different observers to obtain slightly different results. In addition, some of the difference in variability may be related to "splitting" or "lumping" of years in regions of weaker annual signals. (For some time series analyses, the changes in variability in a hybrid time series produced by several observers might introduce spurious results. We thus have prepared a Holocene time series based solely on observations by R.B.A., and we have begun to analyze it statistically; [*Alley et al.*, 1995; *Spinelli*, 1996].)

## 7. Conclusions

Visible stratigraphy has proven to be a useful dating tool for the GISP2 deep ice core, to roughly 50 kyr B.P., and agrees with independent age assessments within their level of accuracy prior to historical records. The signal of depth-hoar complexes was used in the Holocene. Surface and remote-sensing studies show that the hoar complexes are produced in the upper centimeters of the snow by processes linked to summer sunshine, that they are widespread features of the dry-firn facies of central Greenland that are preserved consistently, and thus that they can be expected to be good annual markers. In the early Holocene/Preboreal, the visible signal was calibrated from depth-hoar layers to visible cloudy bands most probably linked to dust content. Cloudy bands were then counted in the Wisconsinan.

Careful surface preparation and light control are necessary for optimal visible stratigraphy as a dating tool. Failure to do so may degrade the signal to the point that no useful data are obtained. Careful application of technique is essential, with adaptation as needed to adjust for changing signal characteristics.

Comparison of visible-stratigraphic ages to fallout from historical volcanoes over the most recent 2 millennia, to independent ages for the end of the Younger Dryas, to other annual markers in the ice core, and to repeat visible stratigraphy by various observers, indicates accuracy typically at the 1% level over century-length or longer intervals through the Holocene. In the Wisconsinan, comparisons to available absolute time markers and intercomparisons of various layer counts suggest 5% or better accuracy over millennial or longer intervals to perhaps 50 kyr B.P.

Errors may arise from true imperfection of the ice core's climate record, from core-quality problems, or from human error in interpreting the record. Intercomparisons of layer counts show that a human factor does exist, although all counts typically are so close that we cannot choose objectively among different estimates because no significant differences exist. We believe that true climate-record imperfections are scarce or absent for accumulation rates typical of central Greenland and thus that multiparameter counts of multiple cores should allow dating with errors much smaller than 1%; however, the reality of the difficulties in collecting and analyzing such cores probably precludes that level of accuracy over 50 kyr or longer for the forseeable future.

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