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A First Step to Reconciling the GRIP and GISP2 Ice-Core Chronologies, 0–14,500 yr B.P.

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δ^{18}O records from the GISP2 and GRIP ice cores are widely used as benchmark paleoclimate chronologies, but there are significant differences between the two time scales. The present study shows that offsets between the two chronologies over the past 14,500 yr do not accumulate gradually, but appear over two short intervals of 100–200 yr. An initial offset of 80 yr occurs close to 3300–3400 yr B.P., and another 100 yr of slip appears at the start of the Younger Dryas. Since these discrepancies are localized, resolving them may be far easier than if large sections of both cores required reexamination.

INTRODUCTION

Two of our most valuable paleoclimate archives are the GISP2 and GRIP ice cores, drilled 30 km apart at Summit, Greenland, in the early 1990s. The δ^{18}O records from the cores (Grootes *et al.*, 1993; Stuiver *et al.*, 1995; Johnsen *et al.*, 1992; Dansgaard *et al.*, 1993) are crucial because they are used extensively for cross-correlating the annual-layer ice-core time scales with uncalibrated paleoclimate sequences, thereby providing North Atlantic, hemispheric, and perhaps even global chronologies for the dramatic climate changes of the Pleistocene–Holocene transition. Unfortunately, the GISP2 and GRIP chronologies disagree by 80 yr at the early Holocene 8200 yr B.P. cold event and at the end of the Younger Dryas and by 200 yr at the start of the Bølling Interstade (Fig. 1). The discrepancies are well within the layer counting uncertainties of 1–2% for the past 14,500 yr (Johnsen *et al.*, 1992; Alley *et al.*, 1997; Meese *et al.*, 1997), but these systematic offsets are nevertheless a major problem for a paleoclimate community increasingly concerned with centennial and even decadal climate change.

An obvious hypothesis is that the offsets are due to the accumulation of small errors in identifying and counting annual layers, leading to a slow incremental shift between the chronologies for the two cores; but surprisingly, this is not the case. This paper reviews evidence from cosmogenic isotopes and ice-core acidity records which identifies an interval between 3000 and 3400 yr B.P. during which most of the 80-yr Holocene offset appears. δ^{18}O data are then used to further constrain this "slip" to a period around 3300–3400 yr B.P. and to identify an additional 100-yr discrepancy at the start of the Younger Dryas. These short intervals supply almost all of the offset between the two chronologies over the past 14,500 yr. Identifying such localized problem areas is a first step toward diagnosing the causes of the offsets and reconciling the two time scales.

GISP2 AND GRIP CHRONOLOGIES

The GISP2 chronology was constructed primarily using δ^{18}O measurements, visual stratigraphy, laser scattering from particulates, and electrical conductivity to identify annual layers, plus additional comparisons with chemical stratigraphy (Alley *et al.*, 1997; Meese *et al.*, 1997). Layer counting was continuous back to 40,000 yr B.P. except for short breaks (typically corresponding to 10 yr or less) due to core loss, mostly in the brittle ice zone ca. 3000–9000 yr B.P. The lengths of these lost sections were known from drill logs, and layer thicknesses were interpolated to estimate the number of lost years (Alley *et al.*, 1997).

The ss09 time scale, the most widely used of the three GRIP chronologies (Johnsen *et al.*, 1992; Dansgaard *et al.*, 1993; Hammer *et al.*, 1997), was determined back to 8600 yr B.P. by correlating volcanic acid fallout horizons with corresponding features in the layer-counted South Greenland Dye 3 core (Hammer *et al.*, 1986). Before 8600 yr B.P., seasonal variations in concentrations of microparticles and several chemical species were counted to establish an annual chronology back to 14,500 yr B.P. For the deeper sections, a relationship between δ^{18}O and ice accumulation rate was assumed and an ice flow model was used to estimate layer thinning (Dansgaard *et al.*, 1993). A combination of the modeling results and tie points from the layer count was then used to develop the final time scale (Johnsen *et al.*, 1992; S. Johnsen, personal communication).

Both chronologies explicitly define the zero B.P. time point as 1950, not the start of ice drilling in 1989, so none of the offset is due to differences in age conventions.

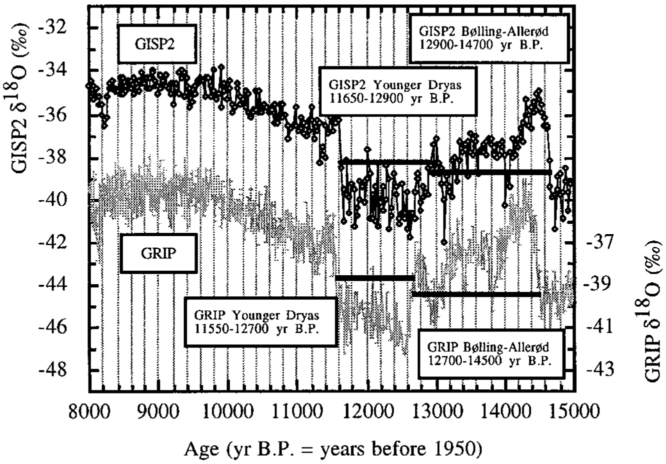

FIG. 1. GISP2 and GRIP $\delta^{18}O$ data (as per mil deviations from the Pee Dee Belemite standard) for the period 8000–15,000 yr B.P., showing temporal offsets between the two chronologies increasing from 80 yr at the early Holocene 8200 yr cold event to 200 yr at the start of the Bølling Interstade.

VOLCANIC ACIDITY SPIKES

Acidity records from GISP2, GRIP, and Dye 3 contain volcanic sulfate spikes which can be detected by measurements of electrical conductivity (ECM) or sulfate concentrations (Clausen *et al.*, 1997; Zielinski *et al.*, 1994). Large peaks at 2000 ± 3 yr B.P. and 3028 ± 5 yr B.P. are essentially synchronous in all three cores, but GISP2–GRIP correlations around 3400–3500 yr B.P. and earlier are less obvious. A group of four sulfate peaks spanning 3391–3409 yr B.P. in GISP2 can be correlated with Dye 3 ECM peaks at 3389, 3406, and 3412 yr B.P., but the GRIP record contains only one large ECM peak in this region at 3374 yr B.P. ECM peaks at 4001 and 3994 yr B.P. in Dye 3 and GRIP, respectively, have no obvious counterpart in GISP2.

Four major GISP2 sulfate spikes between 3550 and 3650 yr B.P. and possibly correlative GRIP and Dye 3 ECM singlets at 3585 and 3593 yr B.P., respectively, have received particular attention. This is due to interest in possible associations between acidity peaks, anomalously cold–wet climate signals in tree rings from 3577 yr B.P., and the Minoan eruption of Thera/Santorini (Manning, 1998; and references therein; Zielinski and Germani, 1998). Baillie (1996), Clausen *et al.* (1997), and Zielinski and Germani (1998) selected peaks at 3619, 3645, and 3573 yr B.P., respectively, as the GISP2 features which correlate best with some or all of the eruption, the climate event, or the ECM peaks. The arguments for the various choices are in some cases complex and are discussed in detail in those papers; suffice it to say there is continuing disagreement. Thus even for this intensively studied interval, the relationship between the GISP2 and GRIP acidity records remains unclear.

GISP2 ^{10}Be vs TREE RING ^{14}C

Both ^{10}Be and ^{14}C are produced in the atmosphere by cosmic rays, but deposition of ^{10}Be is prompt, with an atmospheric lifetime of about 1 yr (Raisbeck *et al.*, 1981), while the recycling of ^{14}C via exchange between carbon reservoirs causes atmospheric ^{14}C concentrations ($\Delta^{14}C$) to lag centennial-scale production changes. Carbon cycle models predict that tree-ring records of atmospheric ^{14}C fluctuations should lag ice-core ^{10}Be variations by 15–20 yr (Stuiver and Braziunas, 1993; Bard *et al.*, 1997), and a 15-yr shift has been seen over the past 1000 yr in Antarctic ice (Bard *et al.*, 1997). However, the published GISP2 record of ^{10}Be concentrations (Finkel and Nishiizumi, 1997), which covers the period prior to 3300 yr B.P., leads the tree-ring $\Delta^{14}C$ record (Stuiver *et al.*, 1998) by 80 yr over the interval 3400–11,300 yr B.P. (Fig. 2). Beyond that time, the ^{10}Be record is perturbed by large ice accumulation rate changes.

As Finkel and Nishiizumi (1997) and Bard *et al.* (1997) have observed, this offset has real significance, because the dendro–time scale for the ^{14}C record is probably accurate to within a year back to 10,400 yr B.P. (Spurk *et al.*, 1998; Kromer and Spurk, 1998; Stuiver *et al.*, 1998). Since it seems unlikely that

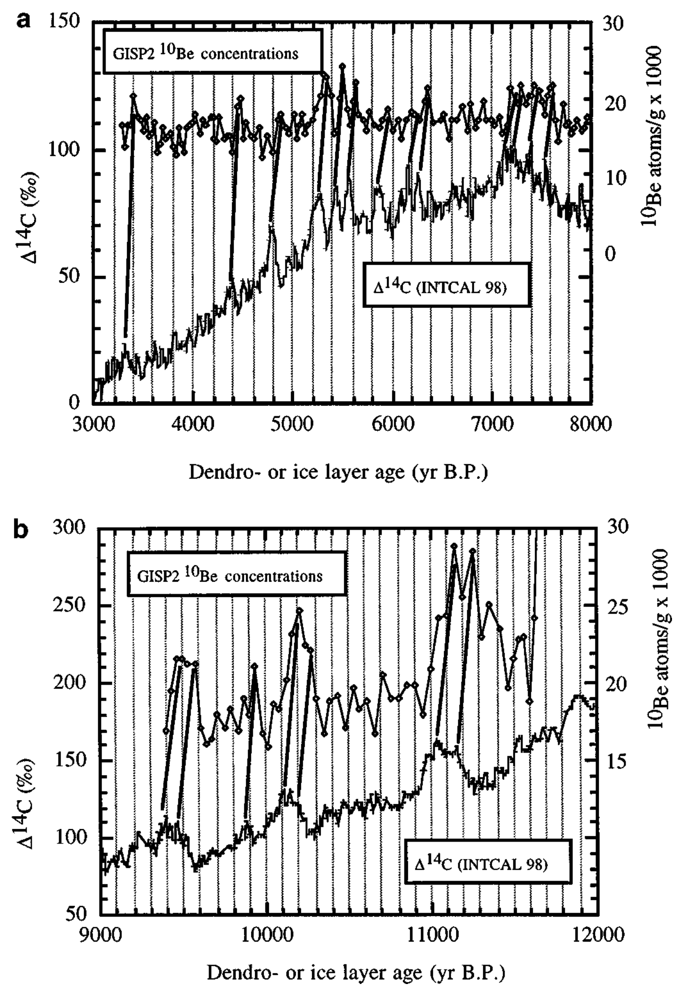

FIG. 2. (a) GISP2 ^{10}Be concentrations versus the INTCAL98 $\Delta^{14}C$ record (Stuiver *et al.*, 1998) for 3000–8000 yr B.P., showing a constant offset of about 80 yr. (b) ^{10}Be–^{14}C comparisons for the older section of the Holocene GISP2 ^{10}Be data.

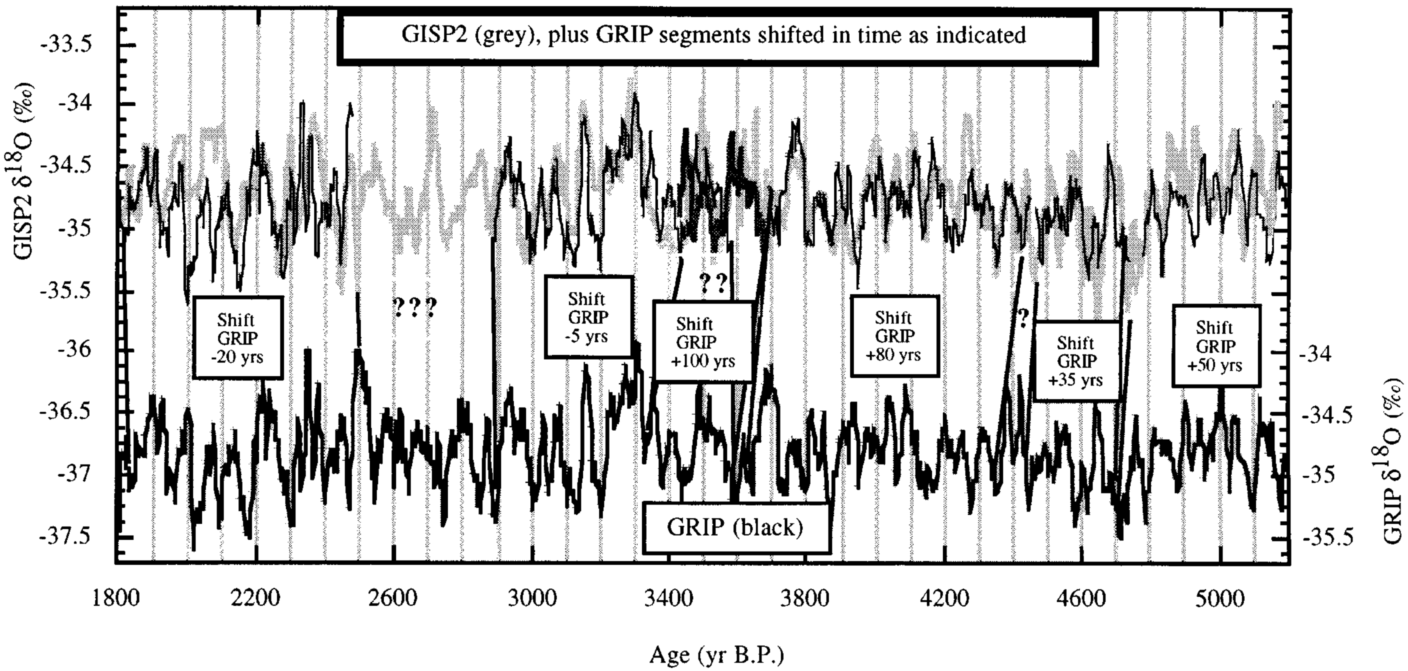

FIG. 3. GISP2 (top) and GRIP (bottom) $\delta^{18}O$ data for 1800–5200 yr B.P. Segments of the GRIP data are also shown in the upper plot, shifted chronologically to correct for estimated GISP2–GRIP offsets and superimposed on the GISP2 results, to illustrate the similarities between the two records. The shifts used are indicated in the figure. Question marks show periods where the two records are poorly correlated (2500–2900 yr B.P. and ca. 4450 yr B.P. on the GISP2 record) or the relationship between the two is ambiguous (3400–3600 yr B.P. in GISP2). Two possibilities for shifted GRIP segments for the period 3300–3600 yr B.P. (shifted by −5 and +100 years, thin and thick black lines, respectively) are plotted over the GISP2 results; see text for further details.

the carbon cycle has changed enough over the Holocene to invalidate the model results, the 80 yr ^{10}Be–^{14}C offset implies that the GISP2 chronology is about 60 yr too old before 3400 yr B.P. (Conversely, the GISP2–GRIP offset of 80 yr at the 8200 yr B.P. cold event and at the end of the Younger Dryas suggests that GRIP could be a decade or two too young in the early Holocene). The ±10- to 20-year stability of this ^{10}Be–^{14}C shift over 8000 yr is remarkable and suggests that the cumulative precision of the GISP2 time scale is far better than the incremental counting uncertainty of 1–2% (Alley *et al.*, 1997; Meese *et al.*, 1997).

More recent work to extend the GISP2 ^{10}Be record toward the present has shown that the equivalent ^{10}Be–^{14}C shifts for prominent ^{14}C peaks at 2300 and 2700 yr B.P. are just 20–30 yr (R. Finkel, personal communication), close to the values predicted by the carbon cycle modeling. Thus, the ^{10}Be–^{14}C evidence points to a stretching of the GISP2 time scale relative to the tree-ring record of the order of 50–60 yr between 2700 and 3400 yr B.P.

GISP2–GRIP δ^{18}O: THE HOLOCENE

Figure 3 shows GISP2 δ^{18}O data (35–40 cm per sample) and GRIP 55-cm results, smoothed with 11-point and 7-point running means respectively to ca. 25-yr resolution. Tentative correlations are shown, and I have shifted segments of the GRIP record chronologically and plotted them over the GISP2 data to illustrate the quality of the fits. The plot extends from the period where acidity spikes show good agreement between the two chronologies, well into the period where ^{10}Be indicates GISP2 is too old.

GRIP data shifted by −20 yr (i.e., to younger ages) fit the GISP2 results reasonably well over most of the period 1800–2500 yr B.P. Gaps in the GISP2 data at 2340 and 2400 yr B.P. are at least partly responsible for the relatively poor fit in the interval 2300–2400 yr B.P. The two records also correspond closely over the period 2900–3300 yr B.P. with minimal shifting, and the region of agreement may extend almost to 3600 yr B.P. (but see below). The GRIP record from 3600 to almost 4400 yr B.P. also bears a striking resemblence to the GISP2 data, but only when shifted by 80 yr to older ages. Thus, the comparison suggests a GISP2–GRIP offset of several decades before the middle of the fourth millennium B.P., but close agreement in more recent times.

The correlations are by no means perfect. The two records bear little resemblance over the period 2500–2900 yr B.P., a result which is surprising but not unprecedented. Stuiver *et al.* (1995) cited other instances of lack of correlation and local variation in δ^{18}O from Greenland cores. Also, significant "accordioning" occurs around 4450 yr B.P.; the offset changes from 80 yr to 35–50 yr, and a prominent double peak at 4400 yr B.P. in GRIP appears to collapse to a single peak at 4440 yr B.P. in GISP2.

Furthermore, the relationship between the two records over the critical 3300–3600 yr B.P. period is ambiguous. The problem is exacerbated by a gap in the GISP2 results from 3420 to 3450 yr B.P. and possibly also by the fact that GISP2 δ^{18}O data from 3484 to 3648 yr B.P. required correction for fractionation due to evaporation from stored water samples (Stuiver *et al.*, 1995). Two alternatives are shown in Figure 3. A minimal (−5 yr) shift applied to the GRIP data captures most of the variations in the GISP2 record at least to 3300 yr B.P. and perhaps almost to 3600 yr B.P., as stated earlier. However, GRIP data for 3330 to 3580 yr B.P. also resemble the GISP2 record when shifted by 100 yr to older ages—a shift at least roughly consistent with the 60 yr indicated by the ^{10}Be–^{14}C comparison at 3400 yr B.P.

In spite of these imperfections, the balance of the δ^{18}O evidence suggests a fundamental change around 3300–3600 yr

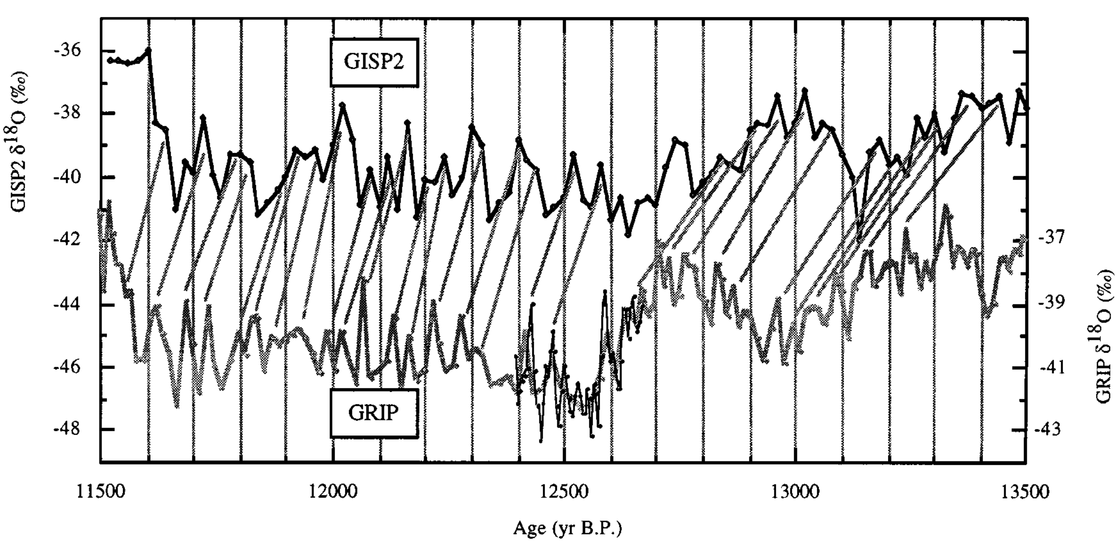

FIG. 4. GISP2 and GRIP δ^{18}O data for 11,000–13,500 yr B.P., showing the increase in GISP2–GRIP offset at the start of the Younger Dryas. Higher resolution GRIP data for the period 12,400–12,680 yr B.P. (shown superimposed on the longer GRIP record) resemble the GISP2 record over the period of slip (see text).

B.P., from GISP2 and GRIP chronologies that agree to within a decade or so to chronologies that are significantly offset. The combination of these results with the ^{10}Be–^{14}C evidence further constrains the period where this offset appears to the interval between 3300 and 3400 yr B.P.

GISP2–GRIP δ^{18}O: THE YOUNGER DRYAS

Figures 1 and 4 compare the 55-cm GISP2 and 20-yr GRIP δ^{18}O data for the Bølling-Allerød-Younger Dryas period. Allowing for minor differences due to finite sampling density and averaging, the agreement between the two records over this period is remarkable, with one major exception: an obvious increase of 100 yr in the GISP2–GRIP offset in the early Younger Dryas. Also shown in Figure 4 are 5-yr GRIP data (S. Johnsen, personal communication) for the period 12,400–12,680 yr B.P., slightly smoothed and plotted over the lower resolution GRIP data. They suggest that the small δ^{18}O peaks or shoulders around 12,620 and 12,670 yr B.P. in the GISP2 record probably have counterparts in GRIP, even though the GRIP 20-yr data in Figure 4 show an almost featureless dip between 12,500 and 12,600 yr B.P. If this interpretation is correct and the two cores do have similar δ^{18}O structure over the entire "slip" period (ca. 12,620–12,850 yr B.P. in GISP2, 12,500–12,650 yr B.P. in GRIP), then the problem is not missing core or other "block" data loss. Rather, the GRIP core lacks about half the annual layers throughout this interval, or the GISP2 ice contains many subannual structures which mimic annual bands, or the layers are in fact annual but one of the counts is erroneous.

CONCLUSIONS

GISP2–GRIP chronological offsets back to 14,500 yr B.P. appear in two short intervals. ^{18}O data from the two cores show good agreement back to 3300 yr B.P., with ambiguous relationships between the two chronologies for the period 3300–3600 yr B.P., and an offset of about 80 yr before 3600 yr B.P. ^{10}Be–^{14}C comparisons show that the GISP2 time scale is in good agreement with dendrochronology at 2700 yr B.P. but appears 60 yr too old before 3400 yr B.P. The combined geochemical data therefore strongly suggest that the GISP2 and GRIP chronologies diverge between 3300 and 3400 yr B.P. This 100-yr period in GRIP is equivalent to 160–180 yr in GISP2. Acidity correlations show that the two time scales agree back to 3000 yr B.P., and although the acidity evidence from before that time is inconclusive, it does suggest a further test. If GISP2 and GRIP are indeed offset before 3400 yr B.P., the identification by Clausen *et al.* (1997) of the 3644 yr B.P. GISP2 sulfate peak with the 3593 yr B.P. GRIP and 3585 yr B.P. Dye 3 ECM peaks is likely correct. Examination of ice from these three peaks for tephra shards of a common composition, regardless of whether this matches any postulated source from Thera/Santorini, would be instructive.

Deeper in the cores, the ^{10}Be–^{14}C data indicate a constant 60-yr offset between the GISP2 and tree-ring chronologies through the early Holocene, and δ^{18}O results from the 8200 yr B.P. cold event and the end of the Younger Dryas show 80- to 100-yr GISP2-GRIP offsets, similar to those present at 3600 yr B.P. The δ^{18}O data also show that the well-known 100-yr discrepancy in the length of the Younger Dryas in GISP2 and GRIP appears right at the Younger Dryas onset. Finer resolution GRIP δ^{18}O data for this period contain structures not unlike those in the GISP2 record, suggesting that the two cores can be correlated across this early Younger Dryas interval but that one of the chronologies is compressed or expanded. For both the Younger Dryas and the Holocene offsets, the GISP2–GRIP discrepancies within the 100–200 yr slip intervals are huge compared to the incremental counting uncertainties, so a mechanism other than small random errors in layer counting is clearly involved.

Because the offsets appear in such localized intervals and because the discrepancies within those intervals are so overwhelming, the chances that the problems can be diagnosed and rectified are increased. Further scrutiny by GISP2 and GRIP investigators of ice, core logs, and other records corresponding to these short periods seems feasible, whereas reexamination and recounting of large sections of both cores would require a huge effort and may even be impossible for some depth intervals if intensive sampling or physical or chemical changes in the ice in storage have led to reductions in core quality.

Apart from these two short problematic intervals, the two chronologies are in remarkable agreement, synchronized to within a few decades over periods as long as 8000 yr. This is a testament to the care with which both chronologies were derived and implies that the incremental counting errors strongly overestimate the cumulative uncertainty over long periods. In turn, this suggests that a unified 14,500-yr Summit chronology of close to decadal precision and accuracy may be achievable once the two problem areas are resolved.

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