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A New Greenland Deep Ice Core

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Summary. The polar ice sheets are rich sources of information on past atmospheric conditions, including paleoclimates. A new deep ice core has been drilled in south Greenland. Comparison of the oxygen isotopic profile with that from Camp Century and with a deep-sea foraminifera record indicates that the new core reaches back to about 90,000 years before present in a continuous sequence. The details in the Wisconsin part of the ice core records seem to be climatically significant, and the general trends reveal all of the relevant Emiliani stages recorded in deep-sea cores. The redated Camp Century record suggests a dramatic termination of the Eem/Sangamon interglacial.

Polar ice sheets are proving to be richer sources of information about past atmospheric conditions than any other sequence of Quaternary sediments. All kinds of fallout from the atmosphere, including airborne continental dust and biological material, volcanic debris, sea salts, cosmic particles, and isotopes produced by cosmic radiation, are deposited on the ice sheet surface along with the snow. The snowpack is gradually compressed into solid ice with small cavities containing samples of atmospheric air. In the coldest areas of the ice sheets, the impurities remain in the ice as indicators of the chemical composition and physical condition of the atmosphere at the time of deposition. Nothing is added, nothing runs off or is displaced, and no chemical reaction takes place; in fact, the composition of the ice layers changes only by decay of radioactive impurities and by extremely slow diffusion processes in the ice crystal lattice.

The ice layers sink into the ice sheet in an undisturbed sequence with continuous horizontal stretching and consequent thinning; in areas with no melting at the bedrock, the ice layers approach zero thickness close to the bottom. This is why, under favorable conditions, an ice core obtained by drilling through an ice sheet can be used to establish continuous and detailed time series of many geophysical and chemical parameters reaching several hundred thousand years back in time: the carbon dioxide concentration in the atmosphere (*1, 2*); climatic changes in terms of accumulation rate (*3*) and, with certain reservations (*4*), surface temperatures (*5, 6*); the chemical composition of the atmosphere (*7*); volcanic activity and its cooling effect in the troposphere (*8*); fallout of cosmic dust (*9*); and the cosmic radiation flux (*1*).

In the past 12 years, many stable isotope [$\delta^{18}O$ (*10*)] profiles have been established along ice cores from both hemispheres. Some of them (*4, 6, 11–13*) reach back into the Wisconsin glaciation. Two of the cores—from Camp Century, northwest Greenland (*11*), and Devon Island, arctic Canada (*12*)—seem to reach through the glaciation and into the Eem/Sangamon interglacial, since close to the bedrock the δ values increase from far below to slightly above Holocene values (see Fig. 1).

In spite of the existence of dating problems beyond 10,000 years B.P. (before present), the Camp Century δ record was exciting, first of all because from a distance, y, of 50 to 230 meters above bedrock it revealed the entire Wisconsin in hitherto unseen detail; see the right-hand section of Fig. 1 that shows the deepest 300 m of the record in 1-m increments. However, only some of the violent δ oscillations from $y = 95$ to 230 m were recognized in the (discontinuous) δ profile from Devon Island (*12*) on the other side of Baffin Bay, and the Antarctic δ profiles (*5, 11*) vary considerably less in the late Wisconsin. Therefore, it remained an open question whether the Camp Century δ oscillations depicted drastic changes in Arctic climate, or should be ascribed to some kind of local effect, such as intermittent changes of the ice flow or opening of the pack ice in Baffin Bay.

Another interesting feature in the Camp Century core was found 29 m above bedrock in high δ pre-Wisconsin ice. A layer only 15 centimeters thick has δ values characteristic of full glacial severity (*14*), as indicated by the dashed line in Fig. 1. Since a similar feature was found in the Devon Island core, the cause can hardly be a local disturbance of the Camp Century stratigraphy. If a climatic interpretation is chosen, it inevitably implies a dramatic cooling of rather short duration, perhaps only a few hundred years. Independent evidence of such an event was later demonstrated in pollen records from northwest France (*15*).

New Greenland Deep Ice Core

The main goal of the joint American-Danish-Swiss Greenland Ice Sheet Program (GISP), 1971 to 1981, was to drill and analyze a new deep ice core to bedrock at the scientifically most favorable location in Greenland. Up to 1976, several ice cores were drilled to shallow (< 100 m) and intermediate (< 1000 m) depths from Peary Land (82.5°N) to South Dome (63°N). Most of these ice cores were drilled on ice divides, which

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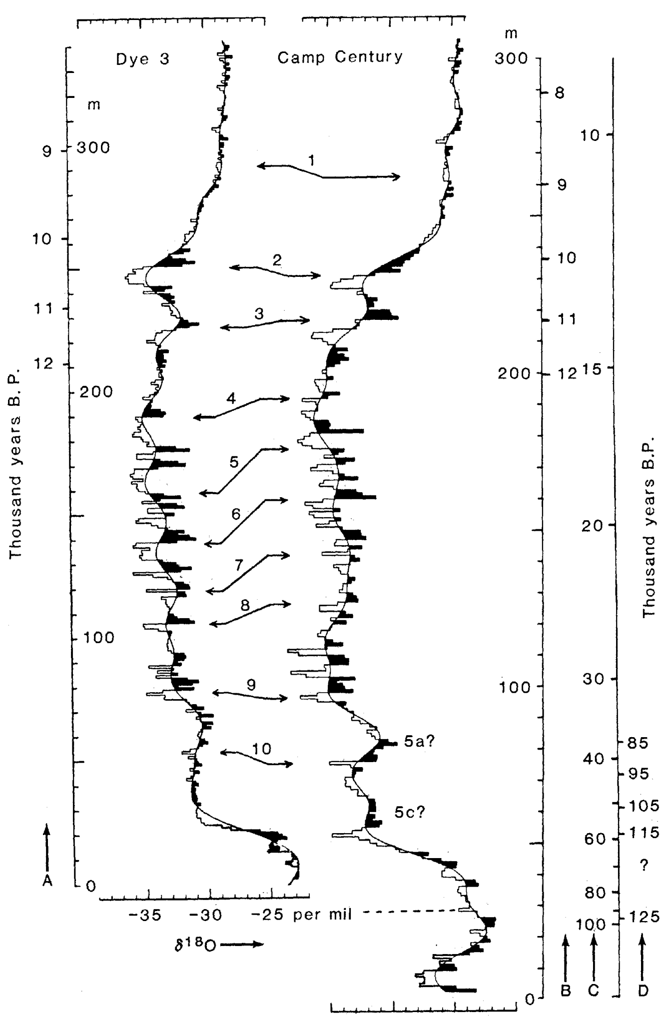
facilitates upstream correction of ice core data (*16*). In the same period, radio echo sounding from airplanes revealed the thickness and the bottom topography of the entire ice sheet (*17*). It appeared that only central Greenland meets all of the seven requirements for a scientifically favorable drill site (*18*). However, for logistic reasons (*19*), and because GISP had to rely on a new deep drill (*20*) that was untested at great depths, the drill site was chosen close to the technically well-equipped Dye 3 station on the south Greenland ice cap (65°N, 44°W). This area does not fulfill all the requirements listed in (*18*) in that the flow line distance to the ice divide is at least 40 kilometers, and the hilly bedrock makes it extremely difficult to design an ice flow model (*21*) that is adequate for upstream correction of deep ice core data.

The deep ice core drilling terminated in August 1981. The ice core is 2035 m long and has a diameter of 10 cm. It was drilled with less than 6° deviation from vertical, and less than 2 m is missing. The deepest 22 m consists of silty ice with an increasing concentration of pebbles downward. In the depth interval 800 to 1400 m the ice was extremely brittle, and even careful handling unavoidably damaged this part of the core, but the rest of the core is in good to excellent condition.

In parallel with the drilling, several physical and chemical analyses were performed, and some 67,000 samples were cut in a continuous sequence for subsequent $\delta^{18}O$ analyses. From 1695 to 1926 m in depth the core was sampled and measured in 5-cm increments, and below 1926 m it was measured in 2.5-cm increments to ensure that no detail in the δ profile would be overlooked. These 8980 δ values have been combined into 1-m mean values, which are shown in the left-hand section of Fig. 1 as a δ profile through the deepest 342 m.

As in the Devon Island core, the Wisconsin to Holocene shift in δ is about 7 per mil. This is considerably less than the 11 per mil δ shift in the Camp Century record, of which approximately 5 per mil may be due to a drastic lowering of the ice sheet surface on the Thule peninsula at the end of the glaciation, possibly in connection with a breakdown of an



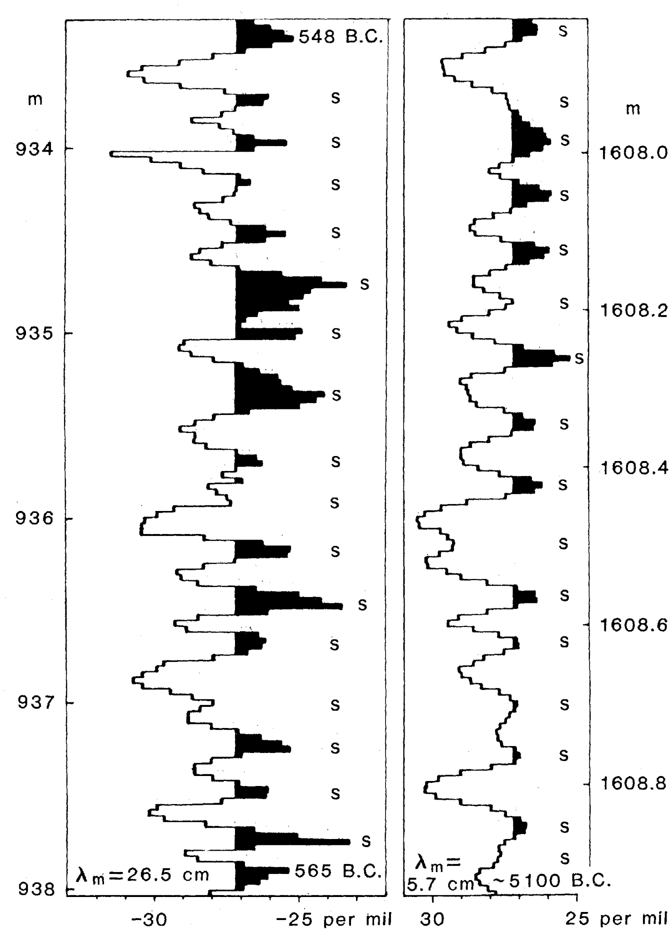


Fig. 1 (left). The deepest few hundred meters of two $\delta^{18}O$ profiles through the ice sheet at Dye 3 in southeast Greenland and at Camp Century in northwest Greenland. The arrows indicate similar details in the two records. The smoothed curves for Dye 3 and Camp Century, respectively, were obtained with 24- and 20-point low-pass digital filters. The deepest—22 and 17 m, respectively—contain silt. The dashed line in the Camp Century record shows a brief drop to δ values characteristic of full glacial severity. This feature has no analog in the Dye 3 core, which does not represent a continuous deposition sequence below 45 m from bedrock. The inner scales show distance from bedrock. Time scales *A* and *B* are deduced from simple ice flow modeling (*24*), *C* from Fourier spectral analyses of the Camp Century record (*30*), and *D* from comparison with a deep-sea record (see Fig. 3). Fig. 2 (right). Seasonal δ variations in two increments from about 936 and 1608 m in depth in the Dye 3 ice core. The present mean annual layer thicknesses, λ_m, are 26.5 and 5.7 cm, respectively. The absolute dating in the left section (548 to 565 B.C.) was obtained by counting δ summer peaks downward from the surface. The δ oscillations were systematically cross-checked by comparison with a seasonally varying acidity profile. Strongly acid fallout from well-known volcanic eruptions (*29*) served as a means for checking the resulting time scale. The right section shows seasonal δ cycles in a deeper increment deposited at ~ 5100 B.C., but not yet absolute dated. The δ cycles are still identifiable, although diffusion in the ice (*28*) has smoothed them to some degree. At more advanced stages of the diffusion process, the δ cycles can be reestablished by a deconvolution technique (*24, 28*).

ice bridge to the Canadian islands (*22*).

When the details in the two δ profiles in Fig. 1 are studied, it appears that essentially all of the δ oscillations in the Dye 3 core down to y = 50 m can be correlated with the previously mentioned features in the Camp Century core down to y = 75 m. This is indicated by the arrows in Fig. 1. In view of the more than 1400-km distance between the drill sites and the completely different ice flow conditions in southeast and northwest Greenland, it seems most likely that the violent δ oscillations in the Wisconsin ice are due neither to any local effect in Baffin Bay nor to any dynamic instability of the ice. They are rather to be ascribed to climatic changes in the North Atlantic region, perhaps to shifts between two different quasi-stationary modes of atmospheric circulation, as suggested by the tendency of the δ's to jump back and forth between −31 and −35 per mil in the Dye 3 record and between −38 and −42 per mil in the Camp Century record.

However, below y = 50 and 75 m, respectively, the two records are completely different. The ice in the Dye 3 core is nearly homogeneous in δ all the way down to the silty ice at y = 22 m, whereas the Camp Century ice continues to vary in δ. The nearly constant δ level through these 28 m of the Dye 3 record is difficult to interpret. It looks as if the drill penetrated in parallel with the isochrons. If this is correct, it suggests a folding of the deepest layers (caused by the complicated ice flow over the mountainous bedrock) and a consequent discontinuity of the time scale along the core (*23*). This is also indicated by the fact that none of the 2000 samples from below y = 50 m show any evidence of the brief dramatic event depicted at y = 29 m in the Camp Century core and close to bedrock in the Devon Island core.

The extremely high δ's in the silty part of the Dye 3 core (up to 4 per mil higher than mid-Holocene values) suggest a warm period of deposition (Eem/Sangamon?), probably with lower surface elevations in south Greenland than exist today. In contrast, the silty ice in the Camp Century core exhibits violent δ variations, dominated by sub-Holocene values, which suggests a pre-Eem/Sangamon time of deposition.

Dating

Holocene ice in Greenland can be dated by many methods (*24*), of which the stratigraphic ones are the most accurate. Under favorable conditions [see point (vi) in (*18*)], it is possible to count many thousands of summer peaks downward in a detailed δ profile. In this way it is possible to obtain an absolute time scale along the core with an accuracy that compares with that of tree ring chronology, particularly if the annual δ cycles are cross-checked against annual cycles in continuous profiles of other parameters, such as acidity (*25*) and concentrations of dust (*24, 26*) or of chemical trace elements (*27*).

Absolute dating of the new Dye 3 core by this technique has so far reached 3600 years B.P., and it will be extended at least twice as far back in time (see Fig. 2). The physical condition of the Camp Century core did not allow measurement of a continuous series of annual δ cycles, but the Holocene part of the core has been dated with rather high precision (*24*). However, diffusion in snow and ice (*28*) puts a limit on the δ cycle counting technique at about 10,000 years B.P. in most of Greenland and at only a few decennia before present in most of Antarctica. Annual acidity cycles cannot be detected beyond 10,000 years B.P. in Greenland either, because the Wisconsin ice is alkaline, but they are detectable far into the Wisconsin ice in Antarctica where the ice is acid all the way to bedrock (*29*).

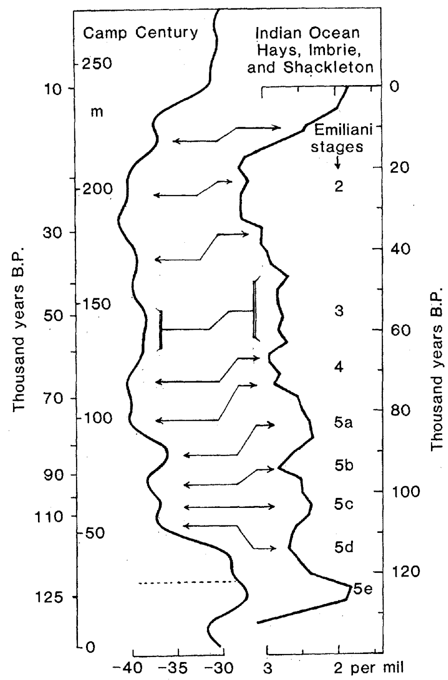


Fig. 3. The upper 4 m of a foraminifera δ record from the subpolar Indian Ocean tentatively correlated with the deepest 270 m of the smoothed Camp Century δ record from Fig. 1. As shown by the arrows, the linear deep-sea time scale to the right is transferred to a new Camp Century time scale to the left; the irregularities of the latter are partly due to accumulation changes in the past. High accumulation rates are suggested around 120,000, 70,000, and 35,000 years B.P., according to the deep-sea record, in periods of buildup of continental ice; the first of these periods seems to have been caused by a drastic but brief cooling, indicated by the dashed line.

Independent dating of the Wisconsin ice in Greenland deep ice cores is a problem. A stratigraphic counting technique may be developed on the basis of measurements of dust or chemical elements that do not diffuse significantly, but this technique is extremely laborious over the time range in question, at least if one aims at absolute dating. Simple ice flow models (*24*) assuming steady state are hardly realistic through much more than the last 10,000 years, and the resulting time scales (*A* and *B* in Fig. 1) have therefore been extended back to only 12,000 years B.P. One likely cause of the deviations from steady state is lower accumulation during the glaciation. This was tentatively taken into account in the Camp Century time scale (*C* in Fig. 1). It was derived (*30*) from Fourier spectral analyses of the preliminary relationship of δ versus time, assuming a persistent 2500-year climatic periodicity. Although this assumption has not been verified convincingly, time scale *C* puts an age of 126,000 years B.P. at the transition from clear to silty ice (y = 17 m), which seems plausible in view of independent dating of deep-sea deposits from the early Eem/Sangamon (*31*). However, this could be fortuitous, and, if it is, the rest of time scale *C* might be far off.

At present, the only rational solution to the problem of independent dating of the deeper parts of the Greenland ice cores seems to be associated with the development of the accelerator–mass spectrometer ^{14}C dating technique (*32*). But the requirements with regard to sensitivity and sample preparation are high because a 70,000-year-old ice increment, 10 m long and 10 cm in diameter, contains only about 0.5 milligram of carbon (in the form of carbon dioxide originally trapped in the air bubbles in the ice), including only about 6000 ^{14}C atoms.

Until the new dating technique is fully developed, it might be worthwhile to try to date the Greenland deep cores indirectly by comparison with records on deep-sea foraminifera, among which the records on benthic foraminifera in particular describe the degree of glaciation, that is, the continental ice volume (*33*).

The right section of Fig. 3 shows the upper 4 m of one of the most intensively studied deep-sea records (*31*), which was obtained by $\delta^{18}O$ analysis of planktonic foraminifera in a core from the floor of the subpolar Indian Ocean. Decreasing δ (to the right) corresponds to decreasing continental ice volume. The linear time scale to the outer right indicates that the curve covers the last 132,000 years. The Emiliani stages (*34*) shown along the record refer to distinct glaciation features that are recognizable in most deep-sea records.

The left section of Fig. 3 shows the Camp Century record from Fig. 1 smoothed by a 20-point (meter) low-pass digital filter in order to obtain approximately equal resolution in the two curves. The tentative correlations indicated by the arrows suggest a close relationship between the two records. A time lag of a few thousand years might be expected, at least in periods of buildup of continental ice—that is, around 120,000, 95,000 and 75,000 years B.P.—because such a buildup (indicated by the deep-sea record) was probably preceded by a climatic cooling. However, in addition to climatic cooling, the Camp Century δ's are sensitive to surface elevation changes associated with the continental ice buildup. Therefore, the time lag between the two records is hardly essential. The time scale of the marine record may therefore be transferred to the Camp Century record in accordance with the arrows, as shown to the outer left in Fig. 3 [the 10,000 year B.P. mark is taken from (*24*)], and, in turn, to the Dye 3 record back to some 90,000 years B.P., as shown in Fig. 4. The reliability of the latter transfer is supported by the fact that fitting the common high-frequency events results in almost identical low-frequency courses of the two (smoothed) curves in Fig. 4. But the resulting ice core time scale is, of course, no closer to absolute chronology than is the time scale along the deep-sea core.

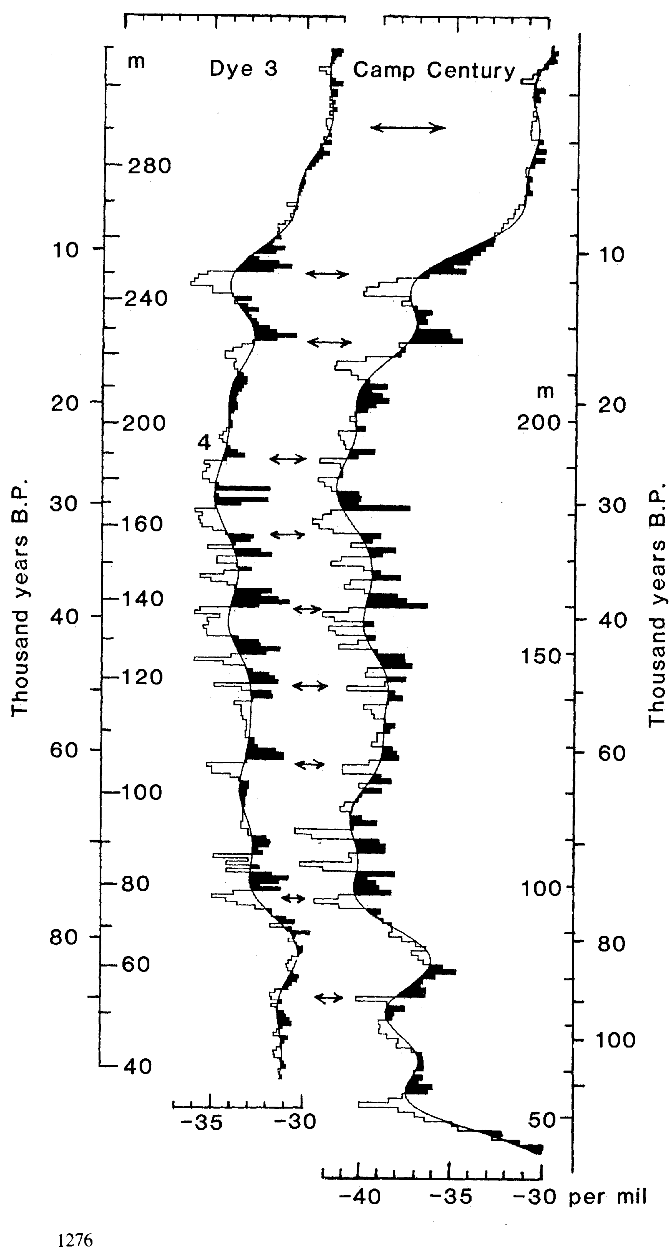


Fig. 4. The Dye 3 δ profile (left) spanning the interval 50 to 260 m from bedrock that is indirectly datable by comparison with the deep-sea record of Hays *et al.* (*31*) through the Camp Century record (right). The 10,000 B.P. marks are from (*24*). The high-frequency δ oscillations have almost the same amplitudes in the two records because they are due to climatic variations, whereas the glacial-to-interglacial shift in δ is smaller in the Dye 3 record because the surface elevation shift was smaller in southeast than in northwest Greenland.

Discussion

The new tentative Camp Century time scale in Fig. 3 is not linear. The 10,000-year depth intervals do not even decrease monotonically downward, as they would in the case of very simple ice flow and accumulation conditions in the past (*35*).

If changing accumulation rate were the only reason for the irregularities in the age versus depth relationship, they would unambiguously indicate relatively high accumulation rates in the intervals 125,000 to 115,000, 80,000 to 60,000, and 40,000 to 30,000 years. These are the intervals during which the deep-sea record indicates considerable buildup of continental ice. It is particularly interesting that the apparently high accumulation rates after the dramatic and brief cooling at about 120,000 years B.P. were associated with ice sheet surface temperatures only slightly lower than in the Eem/Sangamon. This is in agreement with the presence of warm planktonic foraminifera in marine sediments deposited during the periods of ice accumulation from substage 5e to 5d and from 5a to 4, which suggests that the subpolar North Atlantic Ocean between 40°N and 60°N maintained warm surface temperatures during the first half of the ice-growth phase (*36*). All of this would seem to illustrate how it was possible, within the 5000 to 10,000 years succeeding the Eem/Sangamon, to build up some 25×10^6 km^3 of continental ice, as indicated by the deep-sea record, corresponding to a 70-m lowering of the sea level (*37*).

However, the complicated flow history of the ice cap in northwest Greenland contributes to the irregularity of the Camp Century time scale in Fig. 3, and its contribution can be estimated only by more realistic ice flow modeling than is possible at present. The accumulation rate considerations above should therefore be taken with some reservation. They are presented here mainly to demonstrate some of the valuable information that might be obtained from a δ profile through the ice sheet in central Greenland, where the ice flow history is much easier to model and, consequently, the past accumulation rates much easier to determine, at least back to the Eem/Sangamon interglacial. A central Greenland ice core is expected to reach several hundred thousand or perhaps a million years back in time. A δ profile along such a core would reveal several glacial cycles, and although diffusion has gradually smoothed the δ profile downward, as the age and the present temperature of the ice increase, the less diffusive impurities should still reveal the details of the record, particularly since the deposition conditions in central Greenland are ideal.

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19. Any drill site in Greenland has the advantage of being within reach from Thule Air Base or Søndre Strømfjord Air Base, the latter of which has frequent (daily in summer) connections to the United States or Europe. The two Dye sites on the south Greenland ice cap are particularly favorable from a logistic point of view because they have prepared runways for ski-equipped airplanes. The GISP drill site at Dye 3 could be reached in 6 hours by commercial flights from Copenhagen, when needed (never on Sundays, though).
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