tions $\dot{l}_0$, $\dot{g}_0$, $\dot{h}_0$ (*6*, chap. 6, p. 237), as we show in Table 1. To Delaunay's Hamiltonian should be added the function $A = 5/8(\mu/a)m^3\gamma^2e'^2$; hence, we should recover the coefficients in the third column of Table 1 (as produced independently by our theory) by adding to Delaunay's coefficients the partial derivatives of A with respect to L, G, and H, respectively. We checked and did indeed obtain this result.

A number of authors using Delaunay's theory as a check for their theories (*12*) have reported possible errors in his work, but they never pinpointed them. Our conclusion is that, except for the mistakes we uncover here, Delaunay's Hamiltonian and mean motion $\dot{l}_0$ up to order 9 are faultless and the same is true for his mean motions $\dot{g}_0$ and $\dot{h}_0$ up to order 7.

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13 April 1970

Antarctic Ice Sheet: Stable Isotope Analyses of Byrd Station Cores and Interhemispheric Climatic Implications

Abstract. *Oxygen- and hydrogen-isotope analyses from the core hole through the Antarctic Ice Sheet at Byrd Station define temperature variations over more than 75,000 years. Synchronism between major climatic changes in Antarctica and the Northern Hemisphere is strongly indicated. The Wisconsin cold interval extended from 75,000 to 11,000 years ago. Three intra-Wisconsin warmer phases were all colder than pre- or post-Wisconsin times, which suggests that North American and Eurasian continental ice sheets did not disappear at any time during the Wisconsin.*

Oxygen- and hydrogen-isotope analyses of ice samples from depths between 99 and 2162 m within the 2164-m core hole (*1*) of 1968 through the Antarctic Ice Sheet at Byrd Station (80°01′S, 119°31′W, 1530-m elevation) are shown in Fig. 1. The values plotted represent the deviation (δ) of oxygen ($^{18}O/^{16}O$) and hydrogen (D/H) ratios from the corresponding ratios for standard mean ocean water (SMOW). The δ values for both oxygen and hydrogen are here expressed in per mil (*2*, p. 214), even though the δ for hydrogen is not uncommonly given in percent because of its larger magnitude.

Each point on Fig. 1 represents the oxygen or hydrogen δ value of a homogenized strip sample ranging from 30 to 151 cm long taken from the core at intervals ranging between 33 and 62 m, except near the bottom where spot samples were taken. Two or more data points at a single level represent two or more adjoining strip samples. The $\delta^{18}O$ variations, up to 1.5 per mil, in adjacent samples are an expectable product of secular variation, as each homogenized sample represents several years of accumulated snow.

A plot of $\delta^{18}O$ against δD values in Byrd core samples fits a curve, $\delta D = 7.9\ \delta^{18}O$, with slightly different slope than curves obtained from other areas. Since the δD to $\delta^{18}O$ relationship is primarily dependent on temperature, such curves may ultimately prove useful in defining subtle differences and variations in ancient environmental conditions.

In the case at hand, the strong similarity of the oxygen and hydrogen curves (Fig. 1) testifies primarily to the reliability of sampling procedures, sample handling, and analytical methods. Since the two curves are consistent, interpretative comments are made solely in terms of $\delta^{18}O$ data.

Age of ice at various levels is estimated from measured accumulation rates and calculations of thinning through flow, as prescribed by Bader and Nye (*3*, *4*). A constant accumulation of 12 g cm^{-2} yr^{-1} of water is used for the Byrd Station accumulation area. This figure is based on 8 years of measurements made by one of the authors (A.J.G.) at a large number of snow stakes in the vicinity of Byrd Station. These data compare favorably with values of accumulation obtained by other observers who used different measuring techniques (*5*). The calculation of ice ages carries some qualifications. It has been necessary to assume an ice thickness that is constant and a vertical strain rate that remains unchanged. Further, no allowance can be made for possible changes in accumulation rates with past climatological variations. Ages near the bottom are the least reliable because of extreme thinning by flow. The calculations were made independently by A.J.G., largely before he had knowledge of the isotope variations. Our confidence in the results is buoyed by the age (11,000 years) calculated for samples at a depth of 1050 m.

The significance of the isotope curves is that they reflect the relative temperatures at which the water substance composing the samples was condensed. A lower—that is, a more negative—$\delta^{18}O$ or δD value represents a lower temperature. Readers should note that the plot (Fig. 1) is linear for depth but not for age; age increases at an accelerating rate with depth. The data below a depth of 1000 m are plotted against time in Fig. 2.

Only the uppermost part of the ice underlying Byrd Station originates from snow accumulating in the immediate vicinity. With increasing depth, the ice comes from increasingly remote and higher sources. Present terrain configuration and location of the ice divide suggest that none of the ice under Byrd Station is likely to have accumulated in environments more than 300 m higher or 2° to 3°C colder than Byrd Station. The gradual decrease in $\delta^{18}O$ values between depths of 100 and 1050 m (Fig. 1) may reflect, in part, the influence of underflowing ice from distant, colder sources. However, the much larger decrease in $\delta^{18}O$ values between depths of 1050 and 1400 m appears too abrupt and too large to represent anything other than a major climatological change. Only in small degree could it reflect an increase in elevation caused by an increase in ice thickness (*6*). The terrain configuration is not such that a sudden influx of ice from a much colder source, like the South Polar Plateau, is expectable (*7*). The low $\delta^{18}O$ values in the lowermost ice also attest that this ice is not frozen seawater, even though the bottom of the ice sheet is here more than 600 m below sea level.

A significant aspect of the $\delta^{18}O$ curve is the probability that the large change in $\delta^{18}O$ values near the bottom, between 2160 and 2080 m, and the equally large and opposite change between depths of 1400 and 1050 m represent the initiation and termination of the Wisconsin cold interval. The Byrd Station core hole may record all of Wisconsin and post-Wisconsin time.

If age estimates for the Byrd core samples are acceptable, they indicate that the last major Wisconsin cold phase in Antarctica culminated in the neighborhood of 17,000 years ago and terminated about 11,000 years ago. At greater depths, fluctuations in the $\delta^{18}O$ values suggest the possibility of warmer phases peaking at about 25,000, 31,000, and 39,000 years ago with intervening colder phases culminating at about 27,000, 34,000, and 46,000 years ago.

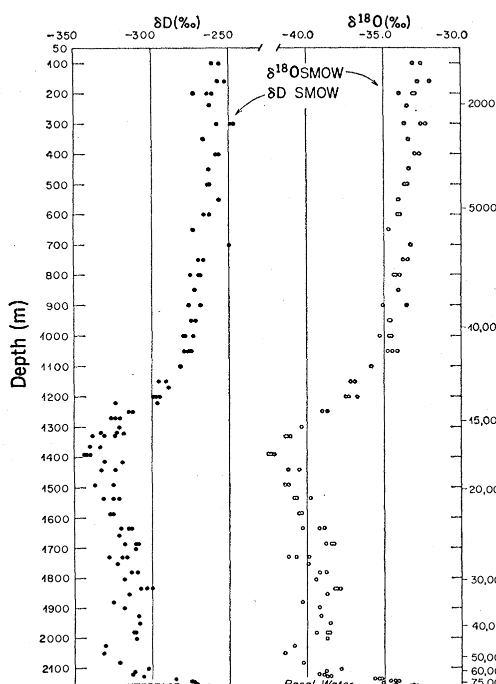
The magnitude of these fluctuations is but a fraction of the change between the Wisconsin and post- and pre-Wisconsin intervals (see Fig. 1). The intra-Wisconsin warmer phases are, however, of considerably longer duration (Fig. 2) than any fluctuations recorded in the post-Wisconsin part of the curve and are possibly of greater magnitude, because the magnitude of δ-value differences now recorded at depth can be significantly less than the initial differences as shown by analyses of δ values in annual layers in a 400-m core from Greenland (*8*). A similar homogenization has probably occurred in Antarctica but has not been independently demonstrated.

The dates of 17,000 years for the culmination and 11,000 years for the termination of the last major Wisconsin cold phase in Antarctica are remarkably close to dates assigned to similar phases of the last major Wisconsin glaciation in North America (*9*). The seeming synchronism of climatologically controlled events in Antarctica and the Northern Hemisphere is one of the more intriguing derivatives of the Byrd Station isotope data. The nature of such interhemispheric relationships has long been of interest to students of glaciation and Pleistocene climatic fluctuations.

The succession of warmer and colder phases recorded in the $\delta^{18}O$ curve below a depth of 1400 m could, with some boldness, be correlated with established intra-Wisconsin stadial and interstadial phases in the Northern Hemisphere. However, the Antarctic data are not yet sufficiently abundant to justify specific correlations of the type suggested by Dansgaard *et al.* (*10*; *11*, p. 221) from the deep core hole at Camp Century in Greenland. Caution is in order because variation in δ values of the magnitude involved could be produced, independently of general temperature change, by a multiple distillation mechanism (*2*, p. 220) involving differences in sources and histories of moisture masses before precipitation occurred in Antarctica. Nonetheless, there is a gross similarity in the pattern of successive intra-Wisconsin warmer and cooler phases in Antarctica and in the Northern Hemisphere.

At depths shallower than 1000 m, the ice formed under warmer post-Wisconsin conditions. A perturbation of the $\delta^{18}O$ curve toward unusual warmth centered at a depth of about 700 m (6500 years ago) might reflect an early phase of the Hypsithermal Interval (*12*), but, aside from that, the Antarctic Ice Sheet seems to have been insensitive to the warmer conditions of roughly 7000 to 4000 years ago widely recognized in the Northern Hemisphere.

If it is granted that the Byrd Station cores represent all of Wisconsin and post-Wisconsin time, the isotope curves (Fig. 1) suggest that the Wisconsin climate in Antarctica was always colder than the post-Wisconsin environment. That is, none of the Wisconsin interstadials approached a true interglacial episode in warmth. This has implications with respect to sea-level fluctuations during the Wisconsin. Recently published data (*13*) suggest that two marine terraces that are, respectively, 4.5 and 2 m above present sea level on



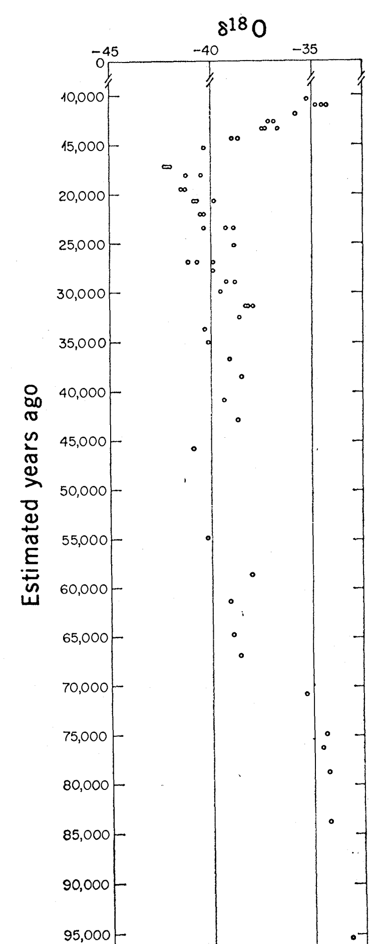


Fig. 1 (above). Oxygen ($^{18}O/^{16}O$) and hydrogen (D/H) isotope ratios, with respect to SMOW, in ice samples from deep core hole at Byrd Station, Antarctica. Linear plot against depth is at left; nonliner plot against estimated age, at right. Fig. 2 (right). Oxygen-isotope ratios of Byrd core hole samples from depths below 1000 m plotted on a linear time scale.

the coast of southeastern United States (Georgia) are of Wisconsin age. The Antarctic isotopic data indicate this age is not likely unless the coast of Georgia has experienced a small independent upward movement or unless the Antarctic and Greenland ice sheets experienced unusual wastage independent of climatic amelioration.

Of particular interest is the indication of warmer conditions in the lowermost part of the core (Figs. 1 and 2). The δ values there recorded suggest an environment even warmer than that of recent centuries in Antarctica. Since ice at the bottom of the hole must have come from localities at least 2° to 3°C colder than the Byrd Station site, an adjustment of the bottom δ values for this relationship would make them roughly 3 to 4 per mil less negative than shown (Fig. 1). The δ values older than about 75,000 years (Fig. 2) thus appear to represent true interglacial conditions.

Recent estimates for the date of initiation of the Wisconsin glaciation range up to 130,000 years (*14*). The isotope data from the Byrd core suggest that an age around 75,000 years is more likely, provided that the change from warm to colder conditions indicated near the bottom of the core truly marks the beginning of the Wisconsin.

Comparison of Antarctic ice-core data with Pleistocene temperature variations recorded in sea-floor cores is of interest. Emiliani's (*15*) curve based on oxygen-isotope analyses of fossil pelagic Foraminifera suggests that the Wisconsin was initiated 70,000 to 75,000 years ago, and he advances arguments for regarding the preceding warm period as a true interglacial. The curve of Ericson *et al.* (*16*) is more generalized, but it too shows initiation of cold conditions about 75,000 years ago.

The section of an isotope curve that represents ages of 10,000 to 75,000 years and that is derived from deep ice cores at Camp Century in Greenland (*10*) displays a reasonable resemblance to the Byrd Station curve, although the Camp Century curve is more detailed because it represents many more analyses. It suggests that the Wisconsin cold period was initiated about 73,000 years ago and thus affords another indication of near-synchronism of climatic changes in the Northern and Southern hemispheres.

The significant difference in time-depth relationships of the Greenland and Antarctic cores needs explanation. At Camp Century the ice sheet is thinner (1390 m) than at Byrd (2164 m), and the accumulation rate is higher (31.5 g cm^{-2} yr^{-1} compared with 12.0 g cm^{-2} yr^{-1}). Yet the calculated time interval represented by the Camp Century core is nearly the same as for the Byrd Station core. This occurs because the flow model used to calculate depth-age relationships at Camp Century (*11*) allows for a nonuniform vertical strain rate and a different temperature regime, in which the basal ice is considerably below the melting point (*17*). At Byrd Station, where the bottom ice is at the pressure-melting point (*1*), basal sliding can occur, and the depth-age relationships are more appropriately calculated by the flow model of Nye (*4*).

One of the variables controlling $\delta^{18}O$ values is the condensation temperature of water vapor. This variable provides a qualified means of approximating the temperature difference between Wisconsin and post-Wisconsin times in the environs of Byrd Station. Unfortunately, temperature is not the only variable (*10*). However, if we assume that the other variables, such as elevation (ice thickness), isotopic composition of seawater, and the meteorological behavior and history of air masses, have not changed radically and that the curves relating $\delta^{18}O$ to temperature of condensation in Antarctica constructed by Aldaz and Deutsch (*18*) are reliable, then the temperature difference between Wisconsin and post-Wisconsin time near Byrd Station was of the order of 7° to 8°C. This is clearly larger than the difference of 2° to 3°, for the intra-Wisconsin cold and warm intervals, although an addition of 1° to 2° might be made to allow for the homogenizing effect mentioned earlier. From various lines of evidence, including isotopic data, Emiliani (*19*) concludes that glacial/interglacial temperature differences for the equatorial Atlantic were about 6°C.

Our conclusions are as follows: (i) The Wisconsin cold interval in Antarctica appears to have extended from about 75,000 to 11,000 years ago. (ii) Major climatic fluctuations in the Northern Hemisphere and in Antarctica have been essentially synchronous from the beginning of the Wisconsin to the present. (iii) The Wisconsin was significantly colder in Antarctica than the post-Wisconsin, by perhaps as much as 7° or 8°C. (iv) Warmer intervals within the Wisconsin, peaking roughly at 25,000, 31,000, and 39,000 years ago, were all too cold to qualify as anything other than interstadials within the Wisconsin; their pattern is similar to interstadials recognized in the Northern Hemisphere, but specific correlations do not yet appear justified. (v) Temperature fluctuations within the Wisconsin were all smaller than the difference between Wisconsin and pre- or post-Wisconsin times. (vi) Temperatures warmer than the present prevailed before 75,000 years ago and probably reflect truly interglacial conditions.

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