Six-Year Record of Oxygen and Hydrogen Isotope Variations in South Pole Firn[1]

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Abstract. Direct measurements of snow accumulation at stakes near the South Pole over a 6-year period (1958–1963) provide an unusual opportunity to check the reliability of accumulation and annual-layer determinations by stratigraphic and isotopic methods. The results are gratifying. Agreement between interpretations based on stratigraphic and isotopic data is excellent, and both are consistent with accumulation-stake measurements in nearly all respects. All three procedures indicate an average annual accumulation of 7 cm of water at the South Pole over the 1958-1963 interval. Isotope data suggest that depth-hoar formation may result in relative enrichment in O^{18}. This could come about through partial recondensation of vapor generated within the depth-hoar layer accompanied by escape of residual vapor impoverished in O^{18}.

Introduction. Repeated observations on a network of 36 accumulation stakes established by Giovinetto on January 27, 1958, near the South Pole station provide a means of checking other methods of determining accumulation. On December 23, 1963, nearly 6 years after the stakes were set, Gow dug pits alongside stakes 25 and 29, studied the firn stratigraphy, and collected samples for oxygen- and hydrogen-isotope study continuously to depths of 119 and 128 cm, respectively. These stakes are 1200 m apart and 2 to 3 km to windward (grid NE) of the South Pole station. The 101 samples collected were analyzed at California Institute of Technology. Since interest in rates of accumulation on the Antarctic ice sheet and in various techniques for determining it is currently at a high level, these data are published promptly, although the completed study will include other Antarctic sites. Through reference to accumulation-stake observations, *Gow* [1965] has demonstrated the reliability of his stratigraphic determination of annual firn layers at the South Pole. The isotopic methods give results which are in excellent agreement, although based on a wholly independent variable.

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In an earlier paper [*Epstein et al.*, 1963, pp. 712–714] the methods, uncertainties, and difficulties of identification of annual layers in Antarctic firn were discussed. Other authors have elaborated on this subject [*Gonfiantini et al.*, 1963; *Lorius*, 1964, p. 217–219; *Giovinetto*, 1964, p. 137]. Initial isotope data suggested that annual accumulation at the South Pole might be as high as 15 cm of water, although it was recognized [*Epstein et al.*, 1963, p. 706] that the results from one 80-cm pit, even though possibly correct, could not give an average value of great reliability because of large year-to-year variation in accumulation (Table 1). Recent tabulations [*Crozaz et al.*, 1964, p. 2603; *Picciotto et al*, 1964, p. 393] of annual accumulation rates at the South Pole, as determined by accumulation-stake measurements, stratigraphy, artificial radioactive fallout, and Pb^{210}, show a range from 6 to 7.5 cm of water, and 7 cm of water now seems to be the most widely accepted round figure for average accumulation at the South Pole. Thus, as pointed out by *Crozaz et al.* [1964, p. 2603], *Picciotto et al.* [1964, p. 394], and *Giovinetto* [1964, p. 137–138], the 15-cm figure is misleading.

The oxygen- and hydrogen-isotope data reported herein from two sites indicate an average annual accumulation for the 6-year interval,

TABLE 1. Thicknesses of Annual Layers of Firn As Determined by Different Methods in Centimeters and in Water Equivalents (g cm^{-2} yr^{-1})

	Pit 25			Pit 29		
Accumulation Year*	Isotopes	Stratigraphy	Stake Observations	Isotopes	Stratigraphy	Stake Observations
1963	24 (8.4)	28 (9.8)	25 (8.8)	25 (8.8)	25 (8.8)	24 (8.4)
1962	26 (9.5)	23 (8.6)	21 (7.8)	17 (6.4)	14 (5.2)	15 (5.6)
1961	10 (3.7)	10 (3.7)	13 (4.8)	16 (6.0)	19 (7.1)	18 (6.7)
1960	23 (8.5)	25 (9.3)	37 (13.9)	16 (6.0)	16 (6.0)	16 (6.0)
1959	12 (4.5)	2 (0.7)	−1 (−0.4)	23 (8.5)	20 (7.5)	27 (10.1)
1958	16 (6.1)	20 (7.6)	13 (4.9)	17 (6.5)	28 (10.5)	20(?) (7.3)

* For the sake of simplicity an annual layer is designated by the year in which it mostly accumulates.

January 1958 to December 1963, of 7.1 cm of water. This is essentially the same value as that obtained by direct measurement and by stratigraphic interpretation at these sites.

Discussion of results. Results from direct observations of snow level on accumulation stakes 29 and 25, from stratigraphic studies in pits alongside these stakes, and from oxygen- and hydrogen-isotope analyses of pit samples are represented graphically in Figures 1 and 2. These figures show that the isotopic and stratigraphic methods as applied here confirm and complement each other nicely, as they have in other parts of Antarctica [*Gonfiantini,* 1963, p. 3794; *Lorius,* 1963, pp. 90–94]. Furthermore, the relationship between the D/H and O^{18}/O^{16}

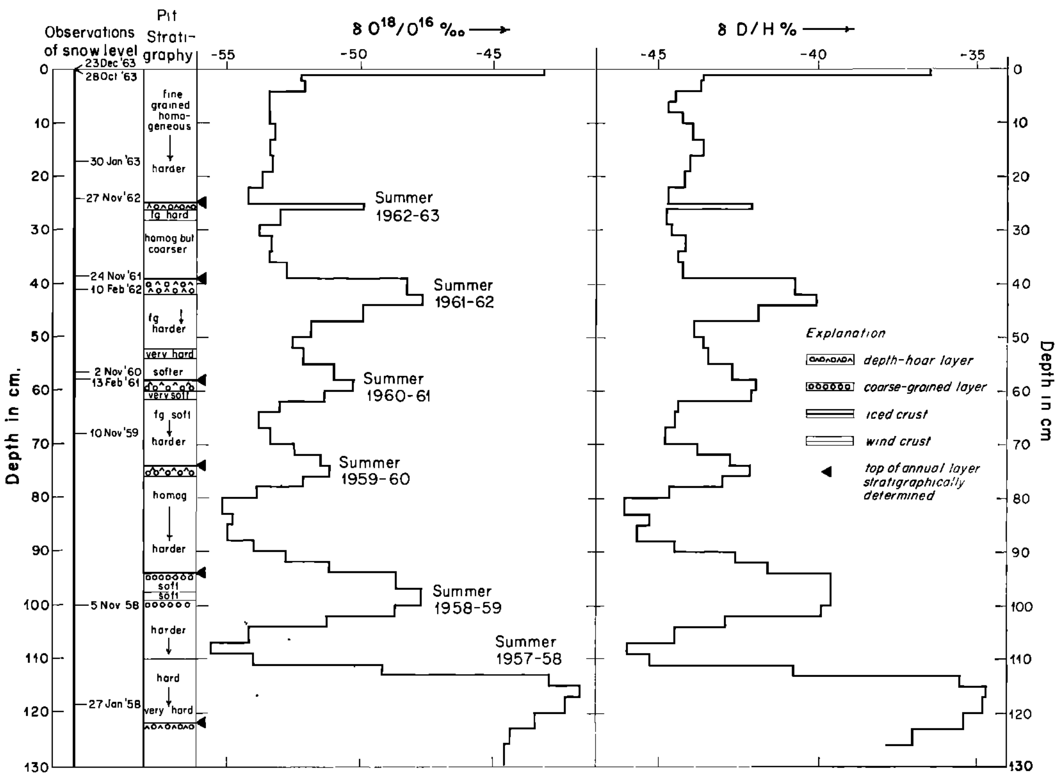

Fig. 1. Data plot for stake 29 in South Pole accumulation network. δ values of O^{18}/O^{16} and of D/H ratios determined as outlined in previous papers [*Craig,* 1961; *Epstein et al.,* 1963].

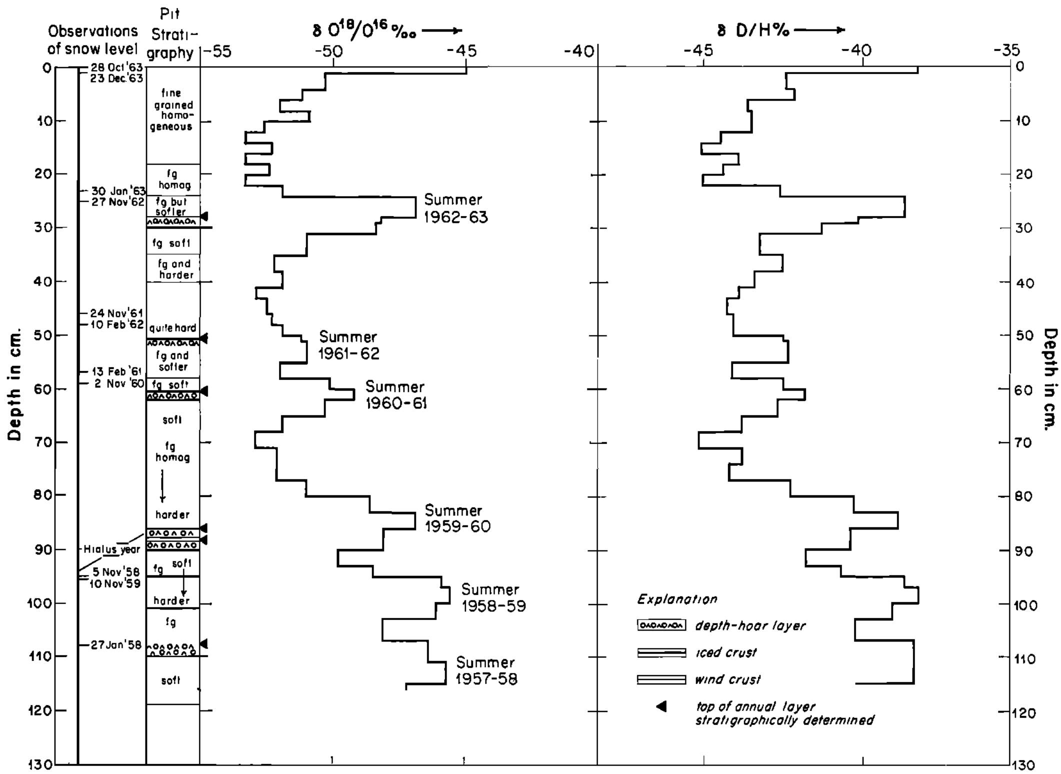

Fig. 2. Data plot for stake 25 in South Pole accumulation network.

ratios of the South Pole and other widely separated sites (Figure 3) is like that obtained by *Craig* [1961] from a large variety of natural precipitation samples. This means that South Pole materials suffered little nonequilibrium evaporation or condensation and that the analyses are correct.

The isotope curves for stake 29 (Figure 1) display excellent agreement with observations of seasonal snow levels at the stake over the 6-year period (1957–1963), the only noteworthy divergence being the stake observation of November 10, 1959. The agreement at stake 25 is nearly as good. An exact correlation to the centimeter is not to be expected, as the pits were necessarily offset about 1 meter from the stakes. The rather small variation in δ values within the thick layers of 'winter' snow and the marked and sudden breaks to 'summer' peaks on the isotope curves for the upper parts of both pits would seem to be consistent with *Gow*'s [1965] statement that most of the accumulation occurs here in winter and that there are essentially only two seasons at the pole, summer and winter, with a relatively sharp transition between. The curves at greater depths are more symmetrical and suggest that nearly one-half the snow was precipitated under relatively warm, although not necessarily summer, conditions.

The lowest part of the oxygen-isotope curve at stake 29 (Figure 1), showing an unusually high peak for austral summer 1957–1958 strongly resembles the curve earlier obtained for the corresponding year on samples from *Giovinetto*'s [1960] pit 11 [*Epstein et al.*, 1963, p. 705]. Stake 29 is approximately 2 km from the site of pit 11, and it is encouraging to find this degree of correlation. A similar correlation was not found in the isotope curves at stake 25 (Figure 2), possibly owing to local factors such as scour and fill. The 1958 samples from Giovinetto's pit 11 have been analyzed for hydrogen isotopes. The analyses confirm the form and detail of the earlier published oxygen-isotope curve. They also show that the previous analy-

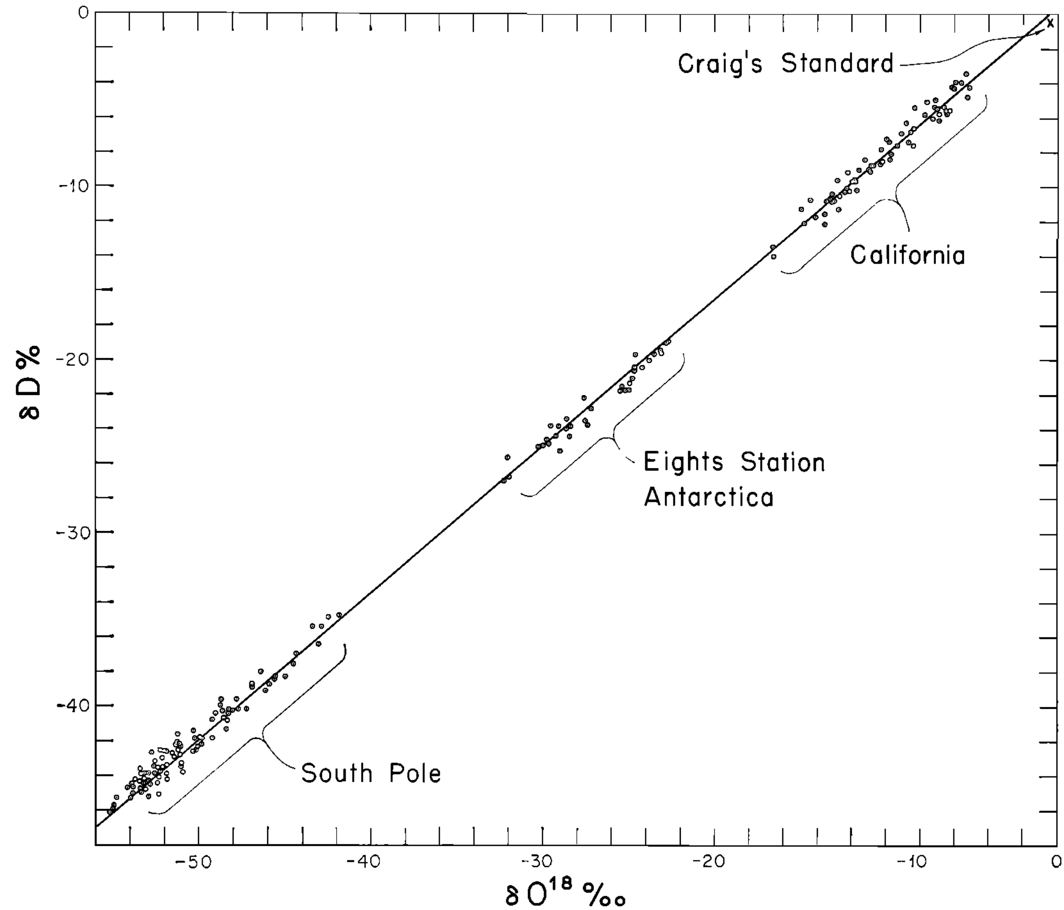

Fig. 3. Graph showing relationship of δD to δO^{18} in precipitation from various localities. Zero on δ scale is standard mean ocean water.

ses were correct and that the samples experienced no significant isotopic change during 2 years of storage in Pasadena.

As to specific considerations, the following are of interest. As shown in Table 1, the number of annual layers identified by the three methods is the same, but thicknesses of individual layers differ. This is not surprising since a year's accumulation as established by stake measurments involves essentially the interval from November to November, whereas stratigraphic determinations are based primarily on depth-hoar layers and isotopic interpretations involve the interval between peaks on isotopic-ratio curves. Thus the time interval represented by a year's accumulation as determined by the three methods can be different both in extent and in the parts of the seasons included. One reason the results agree as well as they do is that much of the snow probably accumulates during the austral winter [*Gow*, 1965].

A principal area of disagreement occurs in the 1958–1960 time interval at stake 25 (Figure 2), where, at a depth of 95 cm stake measurements suggest essentially no accumulation between November 5, 1958, and November 10, 1959, hence the term 'hiatus year.' Stratigraphic studies identify an unusually thick, possibly double, depth-hoar layer near this level which is interpreted as the product of 2 years of near-surface metamorphism of the snow [*Gow*, 1965]. The 5-cm difference in level between this thick depth hoar and the stake measurements may be due to offsetting of the pit from the stake. The disagreement arises because the isotope curves at this depth display excellent seasonal form and give no hint of a significant hiatus in accumulation.

Although stake observations and stratigraphic interpretations are consistent in this instance and therefore favored, the isotopic curves cannot be completely discounted. Once- or twice-a-year observation on accumulation stakes could completely miss an episode of scour and fill, which first lowers and then restores a snow surface. Such a sequence of events could easily have occurred between November 1958 and November 1959. Furthermore, the unusually thick depth-hoar layer at 90 cm might be the product of two or more unusual episodes of metamorphism during exceptional warm periods within a single summer.

The effects of scour and fill are perhaps reflected by relationships at stake 25, where direct measurements of snow level indicate only 2 cm of accumulation from November 2, 1960, to February 13, 1961, in the 57- to 59-cm depth interval. However, the well-defined, reasonably broad isotopic high peaking at 60 to 62 cm suggests that scour may have occurred after November 2, 1960, and was followed by deposition of relatively warm snow which restored the surface to about its original level. Gow believes that the stratigraphic sequence gives no suggestion of such an episode of scour and fill, so the question must be left open. As another example, direct observations at stake 29 suggest accumulation of nearly 7 cm of snow between November 27, 1962, and January 30, 1963, although the isotope curves give no suggestion of a warm snow layer of this thickness at this depth. Possibly the layer was subsequently removed by scour and replaced by cold winter snow.

Special attention has been given to sampling and analysis of loose, coarse-grained depth-hoar layers because of their stratigraphic value. At stake 29 all depth-hoar layers are associated with isotopic highs (less negative δ values) and in 4 out of 7 instances the depth hoar is essentially coincident with the peak of the high.

At stake 25 (Figure 2) the close association of depth hoar and isotopic highs is still clear but less striking. The 1960–1961 and 1961–1962 isotopic highs coincide exactly with depth-hoar layers. However, the depth hoar at 28 to 29 cm is distinctly off the isotopic peak, and the broad, complex depth-hoar zone at 86 to 90 cm is well down the flank of the associated isotopic high. The isotopic peak at 97 to 100 cm has no associated depth hoar; consequently, the isotopic and stratigraphic interpretation are distinctly different at this depth (Table 1).

From these relationships the conclusion is drawn that most depth-hoar layers are associated with high parts of the isotope curves. This could be due to the fact that the snow from which they develop is precipitated under warm conditions or that there is something in the mechanism of depth-hoar formation that results in a relative enrichment of O^{18}. In truth, both explanations may apply. Since depth-hoar layers are reported to develop in snow that accumulated during winter [*Schytt*, 1958, p. 26; *Gow*, 1965], their formation probably involves some O^{18} enrichment.

The formation of depth hoar is not fully understood, but most writers appear to accept sublimation as a process of major importance [*Seligman*, 1936, pp. 68–70; *Schytt*, 1958, p. 25; *Bader*, 1954, pp. 10, 16–17; 1962, p. 8; *Benson*, 1962, p. 26]. The low density, high porosity, and loose aggregation suggest net removal of material during the process, but the large grain sizes with well-defined crystal form indicate growth of the residual grains. Partial sublimation of ice crystals should not significantly change their oxygen-isotope ratio, but partial condensation of vapor can produce an enrichment of O^{18} in the solid phase. Thus, the average δ value of the material ultimately composing a depth-hoar layer will be increased if that material is subjected to sublimation with part of the vapor so formed escaping from the layer and part recondensing therein constituting a depth-hoar layer if we can show that part of the vapor generated within that layer is recondensed and part escapes. The recondensed material is relatively impoverished in O^{18}. Hence, it seems that sublimation with partial recondensation of some of the vapor and escape of the remainder could produce the physical and isotopic characteristics of a depth-hoar layer.

There is always the possibility that a fortuitous occurrence in the accumulation of warm and cold snow, not of seasonal origin, might produce a fluctuation on the isotope curves suggestive of an annual layer. An apparently normal isotopic high between 95- and 103-cm depth at stake 25 might be a case in point. Stake observations showed no accumulation here from November 5, 1958, to November 10, 1959; indeed, the snow level fell 1 cm, possibly through compaction. In this instance an appeal to scour and fill as a means of resolving the disparity is not possible because of isotope values in the underlying firn. The isotopic high involved is not associated with a depth-hoar layer; hence it is also suspect in the eyes of the stratigrapher. However, the validity of this isotopic high cannot be questioned. If it is not of seasonal origin, some other explanation must be found for it.

Conclusion. Interpretations of isotopic and stratigraphic data correlate well with direct observations of accumulation at stakes 25 and 29 of the South Pole network for the 6-year period 1957–1963. An average annual accumulation of 7 cm of water is indicated by all three methods over this time interval. Since stratigraphic methods are easier and cheaper to apply, isotopic procedures may ultimately be used principally to check uncertainties in stratigraphic interpretation or in materials, such as deep cores, where stratigraphic procedures are hard to apply. Isotope studies can, however, provide other useful information bearing on local environmental conditions, secular climatic change, storm paths, the history of air masses, and related matters. With increasing experience and occasional confirmation from actual records, provided by repeated observations on accumulation stakes, it appears that determinations of accumulation rates for the Antarctic are being made with increasing reliability by indirect methods.

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