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Snow Stratigraphy and Oxygen Isotope Variations in the Glaciological Pit of King Baudouin Station, Queen Maud Land, Antarctica

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Abstract. O^{18}/O^{16} ratios have been measured along a firn profile extending from the surface to a depth of 16 meters in the shelf ice of King Baudouin station (East Antarctica, 70°26′S, 24°19′E). Periodical variations are found which are believed to reflect the seasonal variations in the O^{18}/O^{16} ratio of precipitations. They allow the identification of annual layers following the method suggested by Epstein and Sharp. The oxygen isotope variations are compared with the stratigraphic features of the same profile. The notion 'winter' or 'summer' layers is shown to be meaningless when the layers are derived from stratigraphic criteria only. Very often the fine-grained unmetamorphosed layers (generally called 'winter' layers) are made up of snow with high O^{18} content which must represent summer precipitation. On the other hand, the coarse-grained recrystallized layers ('summer' layers) often display a minimum O^{18} content and are composed of snow that fell in the winter. Identification of annual layers involves a similar degree of uncertainty from personal interpretation in the stratigraphic method as well as in the isotope ratio method, but the two methods are complementary, being affected differently by natural circumstances. A good agreement is found between the average accumulation rates deduced from both methods.

Introduction. Precipitations display measurable variations in the isotope ratios of O and H. These variations are mainly functions of geographical and seasonal factors. The general trend of these variations is well explained by the model of fractional distillation proposed by *Epstein and Mayeda* [1953].

The isotope composition of precipitations depends mainly on the temperature at which the precipitation occurs: the lower the temperature, the lower the O^{18}/O^{16} and D/H ratios [*Epstein and Mayeda,* 1953; *Epstein,* 1956; *Dansgaard,* 1954]. At a given location the winter precipitations will be isotopically lighter than the summer ones. This seasonal effect is more striking in the high latitudes and is of special interest on the polar ice caps where the precipitations may be preserved for long periods in their original order of deposition.

The periodical seasonal variations of the O^{18}/O^{16} or D/H ratios can be used to identify the annual snow layers. Such a method would be of great interest in glaciology, as it would enable us to date ice layers as well as to measure accumulation rates even in the absence of any recognizable stratigraphic feature. It has been applied with considerable success to deep cores from the Greenland ice cap by *Epstein and Sharp* [1959]. It relies on two basic principles: (*a*) winter and summer precipitation can be distinguished without ambiguity owing to the difference in their isotope ratios; (*b*) neither the original isotope ratio nor the sequence of deposition of the precipitations is perturbed after deposition.

Our previous papers dealt with variations in the isotopic composition of precipitations collected during 1958 at the King Baudouin station (70°26′S, 24°19′E), Queen Maud Land, Antarctica [*Gonfiantini and Picciotto,* 1959; *Picciotto et al.,* 1960].

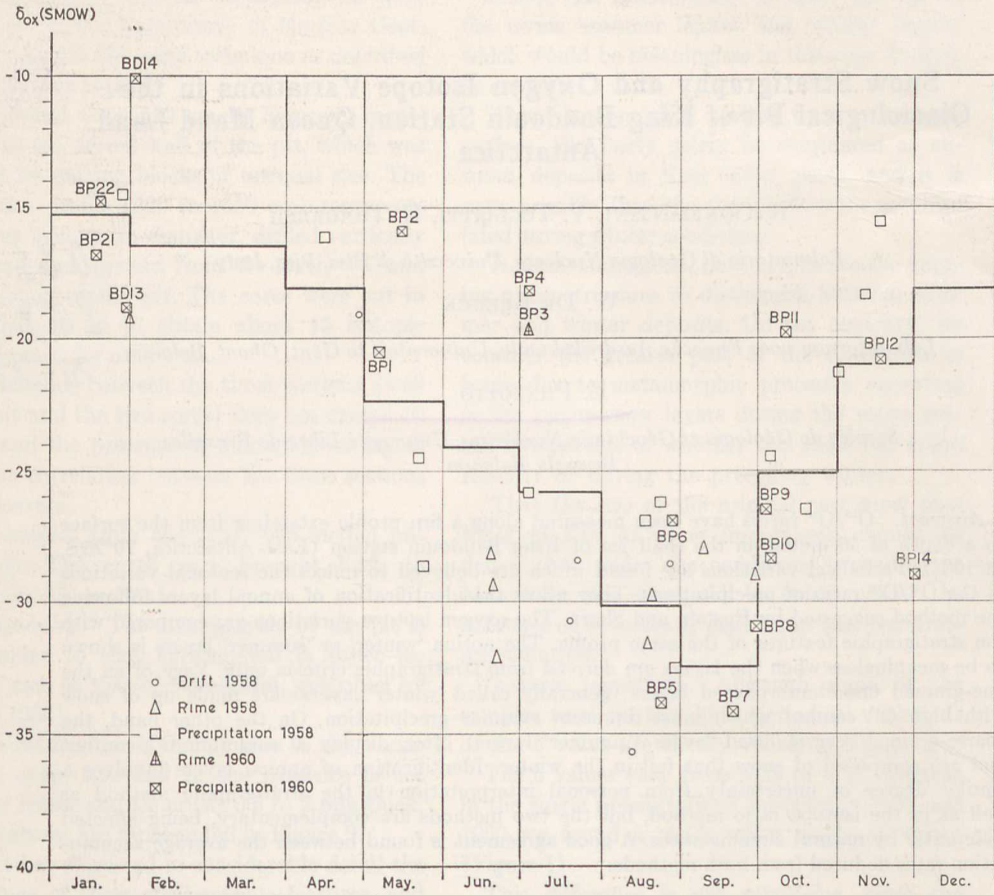

Fig. 1. Precipitation and snow drift samples collected at King Baudouin station during 1958 and 1960. The O^{18}/O^{16} ratio is plotted against calendar time. The monthly average of δ values over the 2 years is given by the solid line.

Seasonal variations were found in accordance with the general scheme, summer snows displaying a higher O^{18}/O^{16} ratio than winter snows.

A similar study has been carried out since on precipitations and snow drift collected at the same site during 1960. Figure 1 shows the variations of the O^{18}/O^{16} ratio of single precipitation and drift samples as a function of the time of collection for both years.

The O^{18}/O^{16} ratio is expressed in the usual way in per mil relative variation with respect to standard mean ocean water [*Craig*, 1961]. The years 1958 and 1960 reveal a similar pattern of variation, but the isotopic seasonal periods are not the same for both years. In 1958 the 'isotopic winter' extended from May through October, whereas in 1960 it began later and included only August, September, and a part of October. In both years the transition from summer to winter seems to have occurred more gradually than the transition from winter to summer.

The work reported here deals with the variation of the O^{18}/O^{16} ratio of firn as a function of depth along a 16-meter-deep profile at King Baudouin station. It is also an attempt to compare these variations with the stratigraphic features generally used to identify annual snow layers.

Sampling and measurements. The samples analyzed were collected in 1960 and described by one of us [*De Breuck*, 1961]. They represent a continuous vertical profile of 16 meters depth in the main glaciological pit of King Baudouin station, dug by Y. van de Can, member of the 1959 wintering party. The zero level corresponds to the summer 1957–1958.

The mass-spectrometric measurements were carried out at the Laboratory of Nuclear Geology at Pisa with the same technique as described in the previous papers.

The section 0 to 520 cm in Figure 2 corresponds to the actual wall of the pit, which was sampled by cutting blocks of unequal size. The rest of the profile (520 to 1550 cm) represents two cores 7.55 cm in diameter, drilled vertically downward and upward from the levels −7 and −9.5 meters of the pit. The cores were cut in 4-cm slices so as to obtain about 15 isotopic measurements for each year.

The distance between the three sections (wall of the pit and the two cores) does not exceed 10 meters and the presence of numerous ice layers made the correlation between the three sections quite accurate.

The samples from th[illegible] were melted immediately. The cores were brought back to Belgium in a frozen state.

Stratigraphy. The stratigraphy of the pit is very similar to that encountered in other ice shelves, such as that of Maudheim, described by *Schytt* [1958].

The stratification is mainly due to the variations in grain size and to the presence of ice layers or lenses and ice crusts 0.5 to 2 mm thick. These features are represented in Figure 2.

Schytt has discussed in considerable detail the significance of these stratigraphic features, and his conclusions are so clearly expressed that we cannot do better than quote them here:

'The pit examined at Maudheim on 30 September 1950 thus showed a definite stratification. The regular appearance of depth hoar horizons on top of ice-rich, water-soaked firn layers with ice-free, fine-grained firn below, left no doubt as to their seasonal origin and made it possible to distinguish annual deposits.

'. . . a "normal" annual layer will be represented in a pit by a coarse-grained, highly metamorphosed summer surface on top of a firn layer of varying grain size and ice content. This firn layer is coarse and has abundant ice pellets and ice layers in its upper part, showing that during a normal summer some melting takes place. This melting, however, is not normally sufficient to produce enough melt water to soak the whole annual deposit and raise its temperature to the melting-point, so that some firn at the bottom remains unsoaked.'

Schytt has intentionally avoided the use of the terms 'summer layers' and 'winter layers,' which would be meaningless in this case. Indeed, he explains:

'These layers, when resting upon a summer surface, can fairly safely be considered as autumn deposits in their lower parts, and it is very possible that the top parts were accumulated during winter conditions.

'It seems impossible, however, to use the varying grain structure to distinguish between summer and winter deposits. On the contrary, we consider the greater part of the coarseness as being due to metamorphic processes operating in the upper snow layers during the warm season irrespective of whether this snow has fallen recently or during the preceding winter.

'That the size of the original new snow particles is also of some importance cannot be denied, but under the conditions prevailing at Maudheim this effect will be hidden under the influence of percolating melt water and penetrating radiation.'

Isotopic variations. Although some of the samples were cut too thick, periodical variations of the δ value are clearly visible in Figure 2.

The δ values vary from −29 to −17, whereas in the single precipitations collected in 1958 and 1960 we found a much wider range of values (Figure 1).

This difference is not surprising, since the accumulation occurs mainly in spring and fall, when precipitations display intermediate values [*Kotlyakov*, 1961]. Moreover, the initially existing variations in δ values may be attenuated by later processes: erosion and wind shift, sublimation, percolation of melt water.

Nevertheless there is no doubt that the periodical fluctuations of δ are mainly due to seasonal variations in the δ of the precipitations. Summer evaporation of melting snow suggested by other authors [*Dansgaard et al.*, 1960] can only play a minor role here, since ice-bearing layers showing evidence of intense melting are not systematically less negative than the others.

In conclusion, layers with a minimum δ value are composed of precipitations occurring during the isotopic winter, which may extend from May to October, and samples with a maximum δ value are composed of precipitations occurring during the isotopic summer, which may last from October to July.

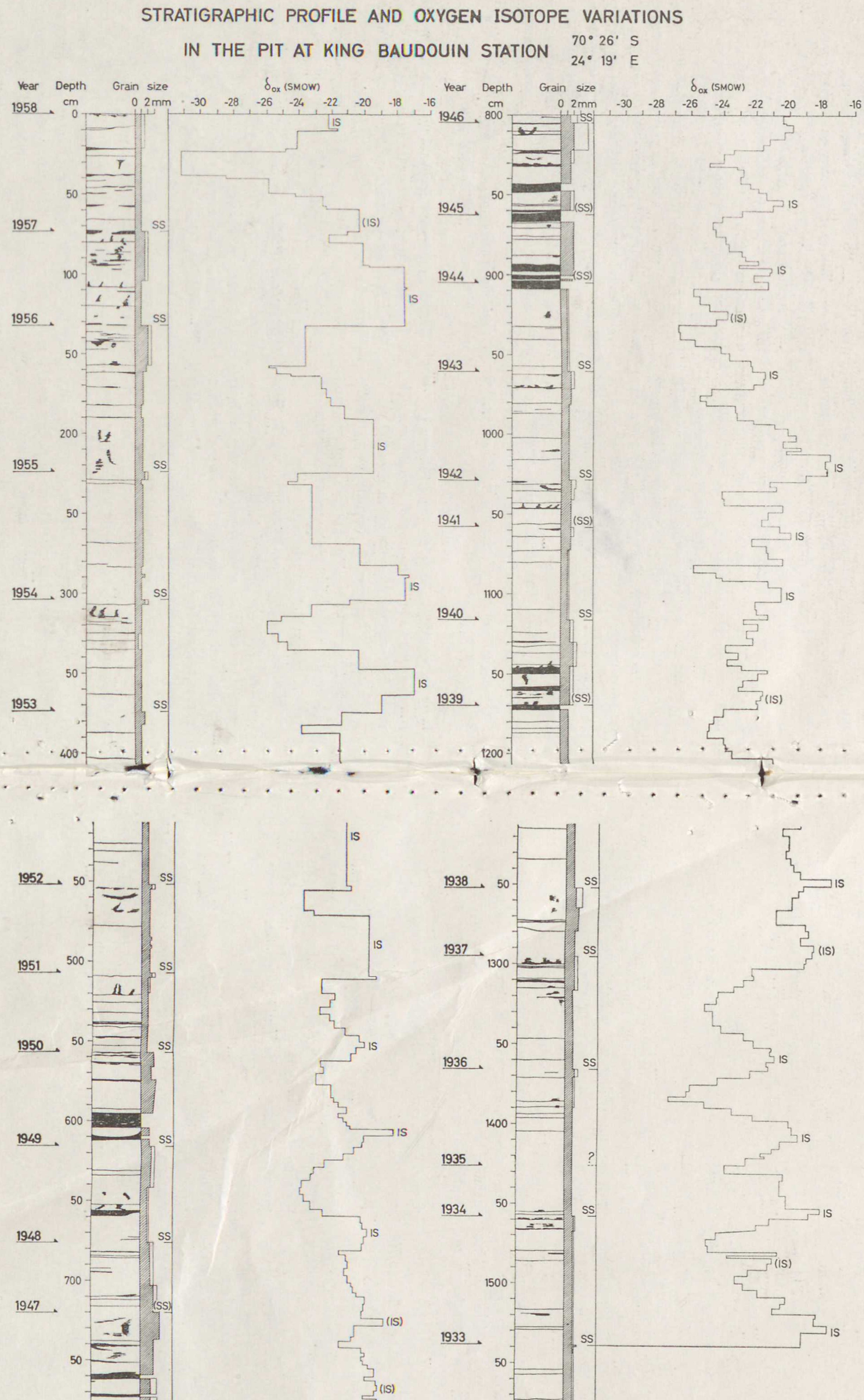

Fig. 2. Stratigraphic profile and oxygen isotope variations in the glaciological pit, King Baudouin station. 1. Ice crust. 2. Ice formation (layer, lens, or infiltration). 3. Average grain diameter. 4. *ss*, position of summer surface; (*ss*), doubtful summer surface. 5. *is*, O^{18}/O^{16} peak; (*is*), doubtful O^{18}/O^{16} peak. The zero level corresponds to the summer 1957–1958. The interpretation in terms of annual layers is given on the left side of the stratigraphic profile.

Discussion and comparison of stratigraphic and isotopic profiles. Other authors have already attempted similar comparisons on shorter profiles [*Lorius*, 1961; *Sharp and Epstein*, 1962]. Their interpretations were apparently based on the idea that the grain size of the firn is directly related to the season during which this snow has fallen, as they made a distinction between coarse-grained 'summer layers' and fine-grained 'winter layers.'

They therefore expected to find the most negative δ values to correspond to the so-called winter layers and the less negative values to 'summer layers.' This interpretation led them to describe any failure in this expected correlation as a discrepancy between the stratigraphical evidences and the isotopic ratio.

We have already pointed out, in accordance with Schytt, that the distinction made between winter and summer layers is meaningless when it is based on morphological criteria. In fact, the only criterion presently available for recognizing the season at which a given layer has been precipitated is its isotopic composition. There is no reason to expect a definite correlation to exist between the grain size or the morphology of a layer and its δ value.

It can be seen in Figure 2 that in almost 70 per cent of the cases the highest δ values correspond to unmetamorphosed fine-grained layers, whereas the low δ values correspond to layers having recrystallized coarse grains and many ice formations.

This apparent contradiction is readily understood when the seasonal pattern of precipitations in Antarctica is kept in mind; accumulation occurs mainly in spring and fall, whereas the middle of the summer and the middle of the winter are periods of low or even negative accumulation.

Most frequently, at the end of the winter, in October, abundant precipitation occurs, followed by a long dry period which lasts until the following fall season. Thus the so-called summer layers are composed of these negative δ winter precipitations which have been exposed to the intense radiation of the sun during December and January.

This interpretation is probably applicable to the whole of the eastern antarctic coast; the fine-grained unmetamorphosed firn layers (so-called winter layers) are generally made up of snow which has fallen at the end of the summer (March, April), whereas the coarse-grained 'summer layers' are composed of snow which has fallen at the end of the winter and has been exposed to the sun in December and January.

It would be advisable to exclude the terms 'winter layers' and 'summer layers' from all stratigraphic description in Antarctica and to use only the term 'summer surface' as defined by Schytt (top of the layer metamorphosed by solar radiation).

As pointed out by Schytt, the time interval between two summer surfaces is variable from year to year: 'It may be as short as 9 months or as long as 15 months. A long term average will be very little affected by this variation, but comparisons between two individual annual deposits may become rather misleading.' The same remark holds for the time between two isotopic minimums or maximums.

Although there is no necessary correlation between the δ value and the morphological features of a given layer, the number of summer surfaces and of isotopic minimums must be identical along a profile involving more than a few years. In other words, the stratigraphic interpretation must result in the same number of years as the isotopic one; otherwise one (or both) of the interpretations is wrong.

Generally, glaciologists tend to consider the isotopic interpretation as the most objective one while physicists have an equal tendency to take for granted the results of the stratigraphic interpretation. Actually, both methods involve some degree of personal interpretation, as is evident in Figure 2.

The summer surfaces are indicated by the lines marked *ss* and the winter isotopic minimums by *is*. When the interpretation is thought to be doubtful, these signs are in parentheses.

Doubts regarding the existence of the summer surfaces may arise either when too intense melting has affected more than a whole year's deposit or from lack of melting or lack of recrystallization.

Doubts regarding the isotopic interpretation are generally due to an exceptionally limited range of variation of δ values. This situation could result from various causes: (1) mixing through melting and percolation of melt water; (2) absence of a winter or a summer deposit owing to lack of precipitation during one of

TABLE 1

	Summer Surfaces	Isotope Peaks
Sure	19 *ss*	21 *is*
Doubtful	5 (*ss*)	6 (*is*)
Maximum	24	27

these periods; (3) removal or mixing of precipitated snow by the wind. Such cases would result in the loss of a δ minimum or maximum with consequent underestimation of the number of years involved.

We have selected from Figure 2 three examples illustrating these various cases:

1. Section 750 to 910 cm shows numerous thick ice layers and evidence of strong melting and soaking by percolating water. This melting, due to hot summer periods, has obviously disturbed both the stratigraphy and the isotope variations over a thickness corresponding to several years to such an extent that it is impossible to interpret them.

2. Between 0 and 160 cm there are two *ss*, but only one *is* is clearly marked. There is a doubtful indication of a second *is* at 65 cm. This situation could be due to normally high temperatures during the summers 1955–1956 and 1956–1957, causing the formation of the two *ss*, and to very poor accumulation during the winter of 1956, resulting in the absence of a winter minimum in the isotopic profile. The stratigraphic interpretation (2 years) is most likely to be the right one.

3. In the section 1320 to 1430 cm, we are dealing with the inverse case; there are two *is* but only one *ss*. The two interpretations seem equally plausible: (*a*) the stratigraphic is the correct one; only 1 year is involved. The superfluous *is* could be due, for instance, to a warm and abundant precipitation during winter time, as has sometimes been recorded (A. P. Crary, personal communication); (*b*) the isotopic interpretation is correct; 2 years are involved. The absence of an *ss* could be explained by an exceptionally cold summer with no surface metamorphism.

Accumulation rate. A count of the summer surfaces and of the isotope peaks yields the results shown in Table 1.

Our preferred interpretation of the profile in terms of annual layers is given in Figure 2, on the left side of the stratigraphic description. It is based both on the firn stratigraphy and on the isotopic ratio data by using the following criteria for the selection of the doubtful cases: (*a*) one certain *ss* or one certain *is* is counted as a year, (*b*) two doubtful evidences simultaneously present are also counted as a year, and (*c*) one doubtful (*ss*) or (*is*) is not taken into account. This interpretation leads to identification of 25 annual layers between the zero level and 1550 cm.

Careful density measurements [*De Breuck*, 1963] result in a water equivalent of 960 cm for the whole column.

The resulting average annual accumulation is *36.7 cm of water*.

Direct determinations of annual accumulation at the same site are available for 1958 [*Picciotto*, 1961] and 1960 [*De Breuck*, 1961].

On the other hand, firn stratigraphy studies made in 1961 led to unambiguous identification of annual layers for the last 6 years [*Tongiorgi et al.*, 1962].

These various results, expressed in water equivalent, compare as follows:

Stake measurements, 1958	20 cm
Stake measurements, 1960	45.5 cm
Firn stratigraphy, 1961–1955 average	39.5 cm
Present work, 1957–1933 average	36.7 cm

It is worth noting that 1958 has been recorded as a year of exceptionally poor accumulation at other eastern Antarctica stations [*Kotlyakov*, 1961].

Conclusions. The information obtained from firn stratigraphy and from isotopic ratio variations are complementary; certain sources of error are common to both methods, for instance, as a result of melting affecting a thickness exceeding 1 year's accumulation.

On the other hand, there are some causes of error which affect them differently. For instance, the absence of precipitation in winter results in the loss of a year in the isotopic profile, but not in the stratigraphic profile. On the contrary, the absence of melting or metamorphosis during exceptionally cold summers would result in the lack of a summer surface and thus in the apparent loss of a year in the stratigraphic profile, but not in the isotopic profile.

Both methods should be used simultaneously, and many further studies of sections in which the stratification is still clearly visible will be required before the isotopic method can be safely applied in layers where the stratigraphy is no longer apparent.

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Addendum. Since this article was prepared, the important paper by *Sharp and Epstein* [1962] was published. It has not been possible to take it fully into account in the present discussion.

References

Craig, H., Standard for reporting concentrations of deuterium and oxygen-18 in natural waters, *Science, 133*(3467), 1833–1834, 1961.

Dansgaard, W., The O_{18}-abundance in fresh water, *Geochim. Cosmochim. Acta, 6,* 241–260, 1954.

Dansgaard, W., G. Nief, and E. Roth, Isotopic distribution in a Greenland iceberg, *Nature, 185* (4708), 232, 1960.

De Breuck, W., Glaciology in eastern Queen Maud Land, Preliminary Report, Third Belgian Antarctic Expedition 1960, *Mededel. Koninkl. Vlaam. Acad. Wetenschap., Belg., Kl. Wetenschap., 23*(6), 15 pp., 1961.

Epstein, S., Variation of the O^{18}/O^{16} ratio of fresh water and ice, *Natl. Acad. Sci. Natl. Res. Council Publ. 400,* pp. 20–28, 1956.

Epstein, S., and T. Mayeda, Variation of O_{18} content of waters from natural sources, *Geochim. Cosmochim. Acta, 4,* 213–224, 1953.

Epstein, S., and R. P. Sharp, Oxygen isotope studies, *IGY Bull.,* no. 21, in *Trans. Am. Geophys. Union, 40*(1), 81–84, 1959.

Gonfiantini, R., and E. Picciotto, Oxygen isotope variations in Antarctic snow samples, *Nature, 184,* 1557–1558, 1959.

Kotlyakov, V. M., Snow cover in the Antarctic and its role in modern glaciation of the continent, *Results of researches on the programme of the IGY, Glaciology,* 9th section of IGY program, no. 7, 245 pp., Moscow, 1961.

Lorius, C., Concentration en deutérium des couches de névé dans l'Antarctique, *Ann. Geophys., 17* (4), 378–386, 1961.

Picciotto, E., Quelques résultats scientifiques de l'Expédition Antarctique Belge 1957–1958, *Ciel Terre, 77*(4–5–6), 126–166, 1961.

Picciotto, E., X. de Maere, and I. Friedman, Isotopic composition and temperature of formation of Antarctic snows, *Nature, 187*(4740), 857–859, 1960.

Schytt, W., Glaciology II, *Norwegian-British-Swedish Antarctic Expedition 1949–1952, Scientific Results,* vol. 4, 148 pp., Norsk Polarinstitutt, Oslo, 1958.

Sharp, R. P., and S. Epstein, Comments on annual rates of accumulation in West Antarctica, *Publ. 58 of the I.A.S.H., Commission of Snow and Ice (Symposium of Obergurgl),* pp. 273–285, 1962.

Tongiorgi, E., E. Picciotto, W. De Breuck, T. Norling, J. Giot, and F. Pantanetti, Deep drilling at Base Roi Baudouin, Dronning Maud Land, Antarctica, *J. Glaciol., 4*(31), 101–110, 1962.

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