

## Strontium 90 Fallout in Antarctica

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**Abstract.**  $\text{Sr}^{90}$  and gross  $\beta$  activities were measured on firn sections collected around Base Roi Baudouin, Scott Base, and South Pole Station. The firn layers were dated by stratigraphy and by oxygen isotope variations. The depth distribution of  $\text{Sr}^{90}$  and gross  $\beta$  activities revealed three radioactive horizons of potential glaciological application. The deepest horizon occurred at the end of 1953 as a result of the fallout of fission products from the Ivy test series, the second and most important one was formed in early 1955 by the debris of the Castle test series, and a third horizon, defined by a sudden increase in the gross  $\beta$  activity but not in the  $\text{Sr}^{90}$  content, was formed at the end of 1962. The rate of  $\text{Sr}^{90}$  deposition over Antarctica has been nearly constant since 1956, amounting to 0.2 and 0.1  $\text{mc}/\text{km}^2 \text{ yr}$  at Base Roi Baudouin and at the South Pole, respectively. The cumulative  $\text{Sr}^{90}$  deposition up to January 1963 in the 70–90°S latitude belt is found to lie between 1 and 3  $\text{mc}/\text{km}^2$ .

**Introduction.** Studies of the  $\text{Sr}^{90}$  distribution in the Antarctic ice sheet allow us to fill a gap in our knowledge of the geographical distribution of radioactive fallout and its evolution with time. No observations have been made between latitudes 53 and 70°S; of the few observations made so far in Antarctica, none was made before 1956.

Moreover,  $\text{Sr}^{90}$  and other radioactive debris from nuclear bomb tests may form well-dated reference levels extending all over the Antarctic ice sheet which are of great interest for glaciological applications [Picciotto *et al.*, 1962].

In previous work Picciotto and Wilgain [1963b] were able to demonstrate the existence, in the snow around the Base Roi Baudouin, of a reference level formed by the stratospheric fallout of radioactive debris from the Castle test series (March–April 1954). This level was formed during the austral summer of 1954–1955, as determined from the interpretation of the stratigraphic and oxygen isotope variations profiles.

Vickers [1963], reached a similar conclusion for other Antarctic localities, interpreting re-

sults published by Libby [1956] and by Drevisky *et al.* [1958].

We have tried to confirm the date of that level and to determine its existence and synchronism over the whole Antarctic continent, in particular on the polar plateau where the measurement of the snow accumulation rate is particularly difficult.

$\text{Sr}^{90}$  and gross  $\beta$  activities were measured on firn sections dated by stratigraphy and oxygen isotope variations, collected in the vicinity of three Antarctic stations: Base Roi Baudouin, Scott Base, and South Pole (see Figure 1). Some of the sections (section A, Figure 2, and section HH, Figure 5) have been extended by precipitation samples collected after the collection of the cores themselves.

**Experimental procedure.** The technique of measurement of the gross  $\beta$  activity has previously been described by Picciotto and Wilgain [1963a].

For  $\text{Sr}^{90}$ , the following procedure was used, for the purpose of simultaneous measurement of  $\text{Sr}^{90}$  and  $\text{Pb}^{210}$ . The samples (5 to 10 kg) were kept frozen from the time of collection until the analysis. A few milligrams of inactive Sr and Pb carriers were added at the moment of melting, together with a sufficient amount of acid to

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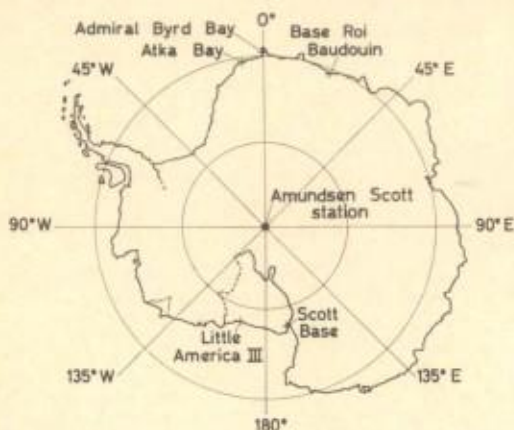


Fig. 1. Location of the Antarctic stations mentioned: Base Roi Baudouin ( $70^{\circ}26'S$ ,  $24^{\circ}19'E$ ), Scott Base ( $77^{\circ}51'S$ ,  $166^{\circ}41'E$ ), Little America III ( $78^{\circ}26'S$ ,  $163^{\circ}50'W$ ), Atka Bay ( $70^{\circ}55'S$ ,  $08^{\circ}06'W$ ), Admiral Byrd Bay ( $69^{\circ}34'S$ ,  $00^{\circ}41'W$ ).

bring the sample to pH 2. These precautions are necessary in order to avoid the adsorption of an important fraction of the radionuclides on the walls of the containers [Picciotto and Wilgain, 1963b; Woodward, 1964].

The first step of the procedure has been described by Crozaz *et al.* [1964]. The effluent from the anion exchange column contains the Sr fraction, which is further purified from the other fission products by differential elution from a cation exchange column (Dowex 50). Inactive Y carrier is added to the Sr fraction. The solution is stored for about 20 days to allow  $Y^{90}$  to reach its radioactive equilibrium with  $Sr^{90}$ .

Y is then separated from Sr in a cation exchange column. The activity of  $Y^{90}$  is measured in a low-level proportional counter; its radiochemical purity is checked by the shape of the decay curve and the absence of residual activity after 20 days. The Sr recovery yield is measured by flame photometry and that of Y by colorimetry with Alizarin-sulfonate.

**Base Roi Baudouin.** In the area of Base Roi Baudouin, we have studied three continuous firn sections collected within a radius of about 5 km around the base (sections A, B, C, Figures 2 and 3).

These sections were collected in 1960 [De Breuck, 1961], 1961 [Tongiorgi *et al.*, 1962], and 1964 [Picciotto and De Breuck, 1964].

Figure 2 shows the stratigraphic as well as

the oxygen isotope profiles which enabled us to date the annual layers without ambiguity. The oxygen isotope results have already been published for sections A and B [Gonfiantini *et al.*, 1963; Gonfiantini, 1965]. Section C has been measured in Brussels and the unpublished results have been kindly communicated by Delwiche and Focroulle.

Figure 3 shows the results of the radioactivity measurements. The gross  $\beta$  activity has been measured on the three sections and the  $Sr^{90}$  activity only on section C. The jump in both the gross  $\beta$  and the  $Sr^{90}$  activities is clearly marked. In the three sections, the jump in the radioactivity starts at a metamorphosed firn layer whose oxygen isotope ratio is characteristic of winter precipitation. This activity reaches a maximum value in an unmetamorphosed firn layer displaying a summer oxygen isotope ratio and overlying the 1954–1955 summer surface.

This implies [see Gonfiantini *et al.*, 1963] that the artificial radioactivity in the precipitations over this area started to increase during the spring of 1954 and reached its maximum value around February 1955 [Picciotto and Wilgain, 1963b].

The  $\beta$  activity below this level is attributable, in major part, to natural radioactive nuclides (1 dpm to  $Pb^{210}$ , 0.7 to  $K^{40}$ ). The small amount of  $Sr^{90}$  detected could be assigned to debris from the Ivy tests (November 1952) and to percolation from the upper layer. Above the 1955 level, the gross  $\beta$  activity (Figure 3, section B) shows more or less periodical fluctuations. Winter snows are usually associated with low activities.

The two additional maximums in the activity in Figure 3, section B, are well marked and correspond to March–April 1957 and to February–March 1959. The date attributed to the second maximum is in agreement with the air radioactivity measurements at Base Roi Baudouin [Picciotto and Wilgain, 1963b] and at South Pole [Lockhart, 1960]. This maximum is very likely due to the fallout of debris from the Hardtack tests (April–June 1958).

The  $Sr^{90}$  to gross  $\beta$  activity ratio was about 20% from 1955 to 1962 and is in reasonable agreement with the value expected for debris which was 6 to 10 years old when the measurements were made [Hallden *et al.*, 1961]. There is one exception in section C; for the depth



interval 7.00–7.85 m this ratio is about 6%. This discrepancy can be explained in several ways: laboratory contamination, higher contribution of natural radionuclides, fractionation of the fission products mixture. The sudden decrease of the ratio after 1962 reflects the arrival of younger debris released by the 1961 and 1962 test series.

*Scott Base.* A continuous firn section was collected in December 1962 in the vicinity of Scott Base, at 2.5 km south of Pram Point [Picciotto and De Breuck, 1963].

The values obtained for the gross  $\beta$  and  $\text{Sr}^{90}$  activities, measured on 80-cm-thick samples, are given in Figure 4. The position of the radioactivity jump has been more precisely located at a depth of  $2.2 \pm 0.1$  m by measuring the gross  $\beta$  activity on 5-cm-thick discontinuous samples.

There is no stratigraphic study nor any determination of the oxygen isotope ratio allowing us to date these samples individually. But, assuming that the jump in the level of radioactivity at 2.2 m corresponds to the beginning of 1955, one obtains an average annual accumulation rate of  $11.4 \pm 1$  cm water for the period 1955–1963. This value is in agreement with the value of 13.6 cm obtained by Stuart and Bull [1963] from measurements in 1959–1960 of eleven stakes located between Pram Point and White Island and with the value of 13.5 cm measured for the period 1958–1962 by Heap and Rundle [1964] in a location very near ours (stake D435).

The attribution of the radioactivity jump to 1955 is further confirmed by Woodward's measurements on samples collected by Heine in the same area and dated by the stratigraphy.

*South Pole.* Two sections, HH (continuous) and P1 (discontinuous), were collected in December 1962 in the vicinity of the Amundsen-Scott Station [Picciotto and De Breuck, 1963]. Section HH was sampled continuously; for section P1 the sampling was performed by coring horizontally in the pit wall every 20 cm with an 8-cm-diameter auger. Section HH was collected 200 m from the station buildings. The accumulation at that point has certainly been affected by the presence of the station, mostly during 1957. This did not happen for section P1, which was collected 1 km upwind from the station.

Figure 5 shows the stratigraphy, the oxygen

isotope profile, and the distribution in depth of  $\text{Sr}^{90}$  and gross  $\beta$  activities for section HH. The interpretation of the stratigraphy, even when complemented by the oxygen isotope profile, leaves an uncertainty of at least 1 year.

The distribution in depth of both the gross  $\beta$  and the  $\text{Sr}^{90}$  activities displays a very sharp increase at a level which cannot be dated with certainty but whose attribution to 1955 is perfectly plausible. A second jump is well marked in 1962, in the gross  $\beta$  activity only.

Figure 6 shows the stratigraphic profile and the gross  $\beta$  activity depth distribution for section P1. Here the interpretation of the stratigraphy appears unambiguous. The rise in  $\beta$  activity occurs in the layer attributed to 1955. One cannot expect the radioactivity profile to be strictly parallel with the one of section HH. The well-marked maximum present in section HH could have been missed either because of the discontinuous sampling procedure or because of the irregularities of the snow deposition in this area.

The mean accumulation rate between 1955 and 1962 is found to be  $6.8 \pm 0.5$  cm water per year, which is in good agreement with other measurements in that region [Giovinetto, 1960, 1964; Picciotto et al., 1964; Gow, 1965].

*Results from other sources.*  $\text{Sr}^{90}$  has been measured in surface snow samples and cores collected by United States Antarctic expeditions in January–February 1955 and 1956 at various localities along the Antarctic coast (Atka Bay, Admiral Byrd Bay, Little America area, McMurdo Sound; see Figure 1). The results are reported by Libby [1956], Drevinsky et al. [1958], and Martell [1959]. Stratigraphic descriptions are generally lacking, as well as details on the experimental procedures used. It is not known whether the necessary precautions were taken to avoid  $\text{Sr}^{90}$  losses by adsorption. Nevertheless, these first results are very interesting because the samples were collected during the main period of the rise in radioactivity or just afterward. They mainly show that the  $\text{Sr}^{90}$  content in the precipitations was already relatively high (2 to 5 dpm/kg) during the summer of 1954–1955.

Vickers [1963] has tried to interpret these data by using rather indirect information on the stratigraphy and the accumulation rates.

Woodward [1964] has measured the  $\text{Sr}^{90}$  and

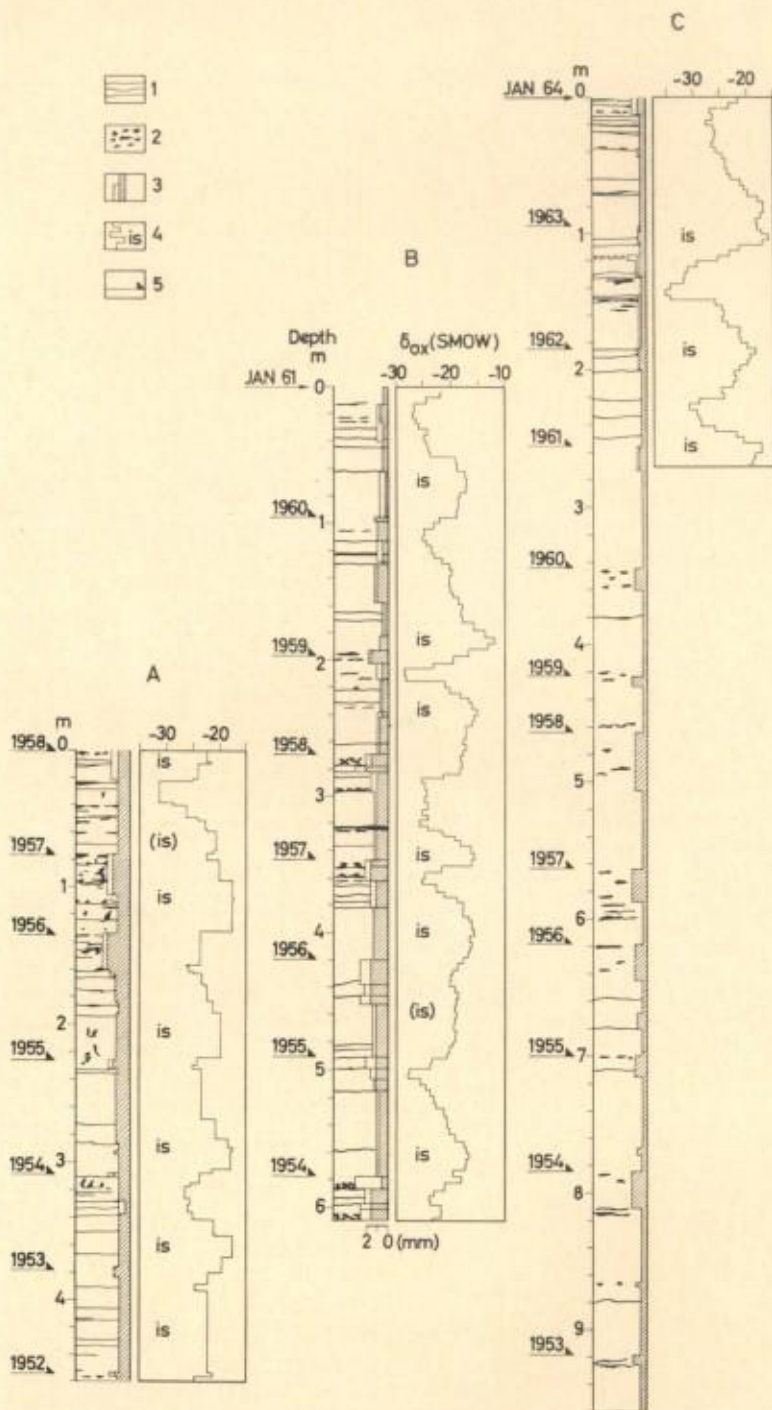


Fig. 2. Base Roi Baudouin, stratigraphic profile and oxygen isotope variations. The three sections have been aligned on the three summer surfaces attributed to 1955. Legend: 1. Icy crust. 2. Ice formation. 3. Average grain diameter. 4. 'is' means  $O^{18}/O^{16}$  summer maximum; '(is)' means doubtful  $O^{18}/O^{16}$  summer maximum. 5. Attributed year.



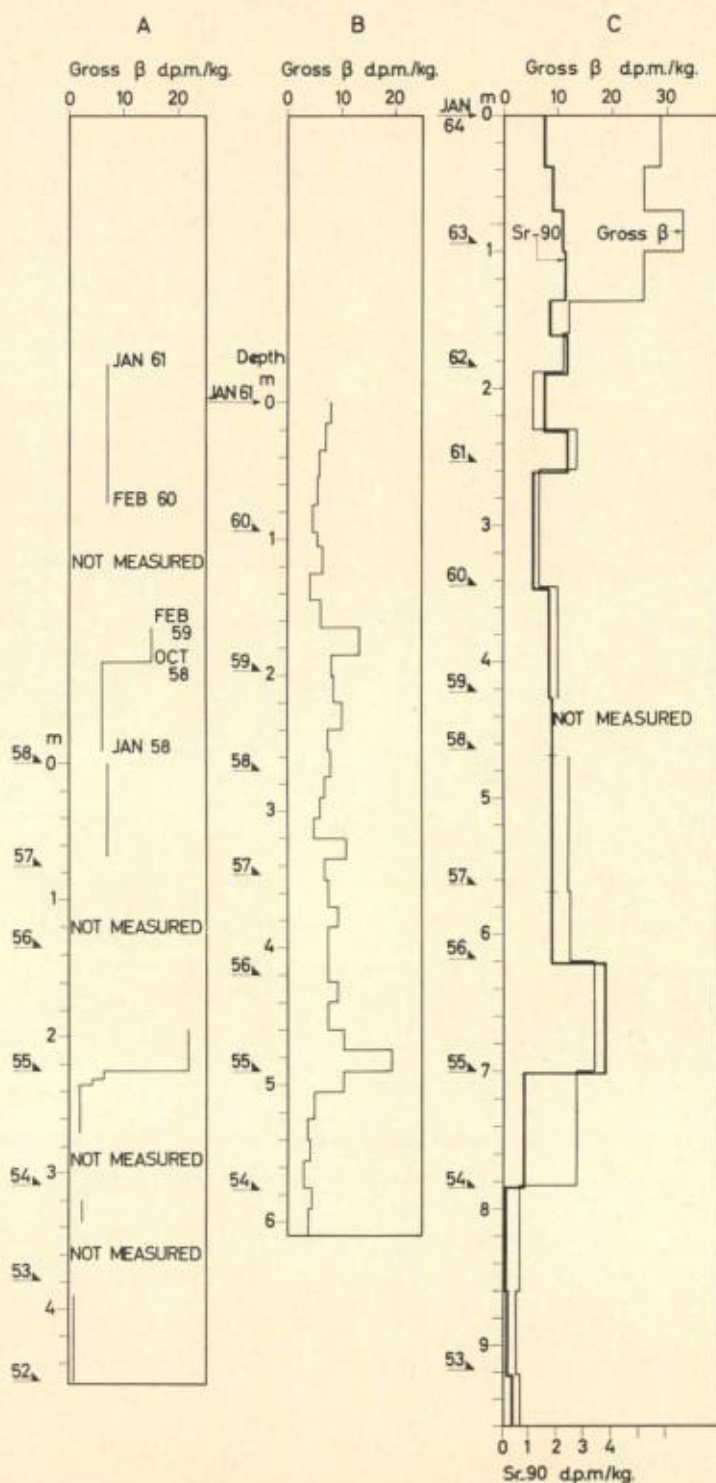


Fig. 3. Base Roi Baudouin, distribution of gross  $\beta$  and  $\text{Sr}^{90}$  activities versus depth. Gross  $\beta$  activity measured in November 1962(A), March 1964(B), May 1964(C). The three sections have been aligned on the three summer surfaces attributed to 1955.

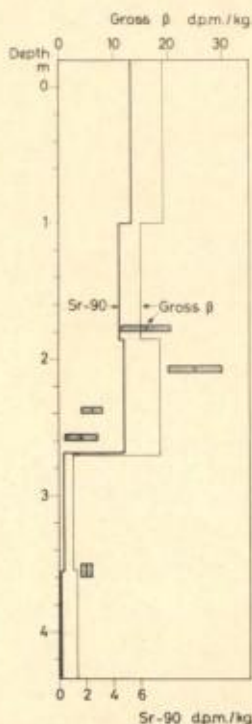


Fig. 4. Scott Base, distribution of  $\text{Sr}^{90}$  and gross  $\beta$  activities versus depth. Gross  $\beta$  activity measured in Feb. 1964. Gross  $\beta$  activity of 5-cm-thick samples is reported with the standard deviation in shaded area.

$\text{Cs}^{137}$  activities in samples from a pit near Scott Base. His results clearly show the adsorption of  $\text{Sr}^{90}$  when the Sr carrier is not added to the sample at the moment of melting. The  $\text{Sr}^{90}$  distribution with depth displays a sudden increase (from 0.5 to 7 dpm/kg) at a level attributed to the second half of 1955.

The dates for the layers that were determined by stratigraphy only, agree excellently with our dates.

**Radioactive reference levels in Antarctica.** On the basis of the evidence presently available, three radioactive reference levels can be recognized in the Antarctic ice sheet. The deepest level is characterized by the first occurrence of  $\text{Sr}^{90}$  in Antarctica, originating from the Ivy bomb test series (November 1952); its date is not accurately known, but it can be placed near the end of 1953. The increase in gross  $\beta$  activity associated with that level is hardly noticeable above the background because of the natural radioactive nuclides (mainly  $\text{K}^{40}$  and  $\text{Pb}^{210}$ ). On the other hand, the  $\text{Sr}^{90}$  activity, although very low (a few tenths of dpm/kg), is always detectable because the natural background is practically zero, but its detection requires large samples (several kilograms).

The second level was formed in early 1955

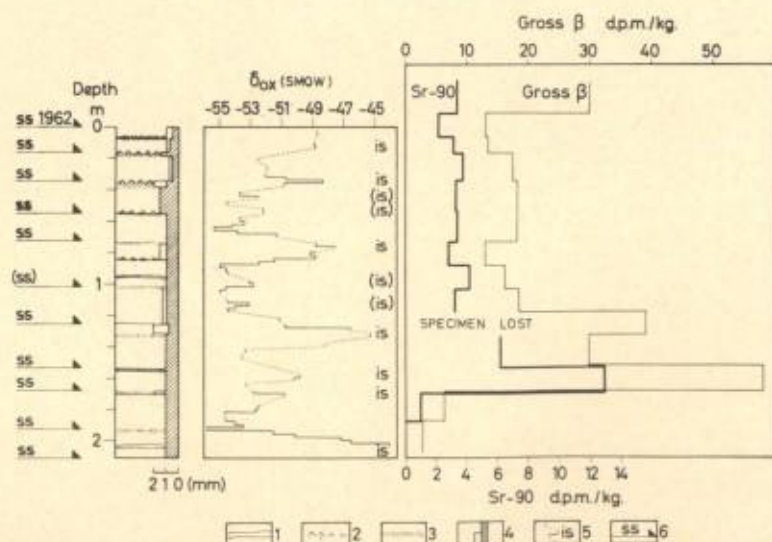


Fig. 5. South Pole, section HH. Stratigraphic profile, oxygen isotope variations, distribution of  $\text{Sr}^{90}$  and gross  $\beta$  activities versus depth. Gross  $\beta$  activity measured in Feb. 1964. Legend: 1. Icy crust, 2. Depth hoar, 3. Loose layers, 4. Average grain diameter, 5. 'is' means  $\text{O}^{18}/\text{O}^{16}$  summer maximum; '(is)' means doubtful  $\text{O}^{18}/\text{O}^{16}$  summer maximum, 6. 'ss' means summer surface; '(ss)' means doubtful summer surface.



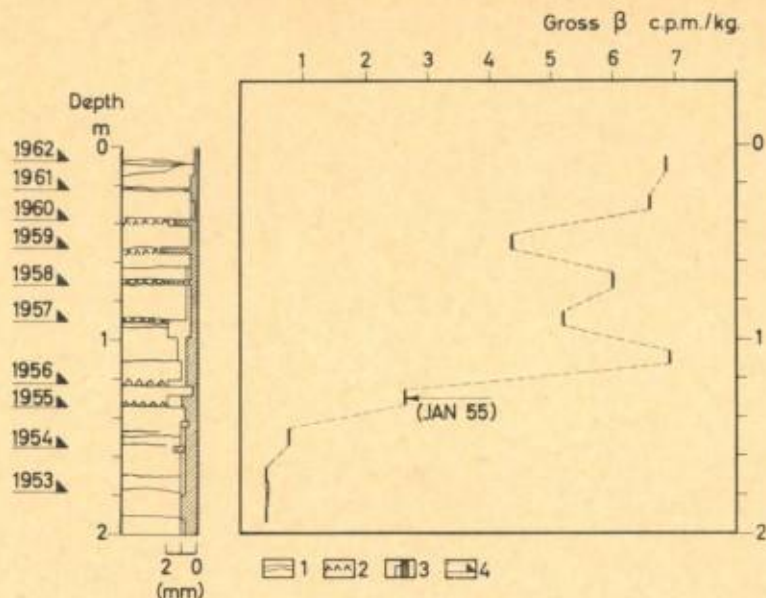


Fig. 6. South Pole, section P1. Stratigraphic profile and distribution of gross  $\beta$  activity versus depth. Gross  $\beta$  activity in arbitrary units, measured in July 1963. Legend: 1. Icy crust. 2. Depth hoar. 3. Average grain diameter. 4. Attributed year.

by the fallout of debris from the Castle test series (March–April 1954). It is characterized by a large and sudden increase both in  $\text{Sr}^{90}$  (2 to 10 dpm/kg) and gross  $\beta$  (20 to 50 dpm/kg)

TABLE 1.  $\text{Sr}^{90}$  in Snow, Base Roi Baudouin

Depth Interval, cm	Attributed Year	$\text{Sr}^{90}$ , dpm/kg
0–40	1963	$1.5 \pm 0.2$
40–70	1963	$1.8 \pm 0.2$
70–100	1962–1963*	$2.2 \pm 0.2$
100–135	1962	$2.3 \pm 0.2$
135–160	1962	$1.7 \pm 0.2$
160–188	1962	$2.4 \pm 0.2$
188–230	1961	$1.5 \pm 0.5$
230–255	1961	$2.4 \pm 0.2$
255–346	1960	$1.1 \pm 0.1$
346–426	1959	$1.7 \pm 0.2$
426–466	1958	$1.8 \pm 0.2$
466–566	1957	$1.8 \pm 0.2$
566–620	1956	$1.8 \pm 0.2$
620–700	1955	$3.8 \pm 0.5$
700–785	1954	$0.8 \pm 0.1$
785–860	1953	$0.1 \pm 0.1$
860–925	1953	$0.2 \pm 0.1$
925–960	1952	$0.4 \pm 0.1$

\* Summer.

activities, the latter being easily measurable in 100-g samples.

The third level occurred in late 1962 and resulted from the resumption of nuclear bomb tests in the atmosphere in September 1961. It is marked by a jump in gross  $\beta$  activity only and not in the  $\text{Sr}^{90}$  activity. This third level is due to the arrival of young debris with relatively short half-life, and it consequently will fade out and disappear completely a few years from now.

The second level, in early 1955, seems to be the best suited for glaciological applications. At present, its detection is still relatively easy on the polar plateau, where it is found at a depth of 2 to 3 m. On the coast, it lies at a depth of

TABLE 2.  $\text{Sr}^{90}$  in Snow, Scott Base

Depth Interval, cm	$\text{Sr}^{90}$ , dpm/kg
0–100	$4.8 \pm 0.5$
100–185	$4.4 \pm 0.4$
185–270	$5.3 \pm 0.5$
270–355	$0.3 \pm 0.2$
355–440	$0.1 \pm 0.2$

TABLE 3.  $\text{Sr}^{90}$  in Snow, South Pole

Depth Interval, cm	Attributed Year	$\text{Sr}^{90}$ , dpm/kg
	1962	$3.4 \pm 0.3$
	1961-1962*	$2.2 \pm 0.2$
6-16	1961	$3.2 \pm 0.3$
16-34	1960	$3.8 \pm 0.4$
34-54.5	1959	$3.3 \pm 0.3$
54.5-73	1958	$3.4 \pm 0.3$
73-88.5	1957	$2.8 \pm 0.3$
88.5-103	1957	$4.2 \pm 0.4$
109-118	1957	$3.2 \pm 0.3$
118-133	1956-1957*	Sample lost
133-153	1956	$6.2 \pm 0.6$
153-168	1955	$12.9 \pm 1.3$
168-188	1954	$1 \pm 0.1$
188-208	1953	$0 \pm 0.1$

\* Summer.

about 10 m, and here the third level may prove to be useful also.

**$\text{Sr}^{90}$  deposition.** This work contributes some information on the  $\text{Sr}^{90}$  deposition in the 70-90°S belt, for which the usual methods of soil or precipitation analysis are ineffective.

We will consider here only the results obtained from three of our firm sections which represent the time interval 1952-1963 and which were collected with the necessary precautions to avoid losses by adsorption. They are section C from Base Roi Baudouin, section RIS from Scott Base, and section HH from South Pole.

The results are given in Figures 3(C), 4, and 5 and in Tables 1, 2, and 3. The  $\text{Sr}^{90}$  values are corrected for the amount of decay since the time of precipitation.

At each location, the  $\text{Sr}^{90}$  concentration and the deposition rate undergo a sudden increase at the beginning of 1955, afterward remaining at a nearly constant value. This trend is very similar to the one observed at other stations in the southern hemisphere [Walton, 1961; Telegadas, 1961; Collins, 1964].

Table 4 gives, for the three localities, the total  $\text{Sr}^{90}$  deposition up to January 1963 and the water accumulation rate estimated from the depth of the main radioactive horizon marking February 1955; these accumulation rates are in good agreement with the values obtained by other methods of measurement. For the South

TABLE 4.  $\text{Sr}^{90}$  Deposition up to January 1963

Location	Total Deposition, mc $\text{Sr}^{90}$ /km <sup>2</sup>	Water Accumulation Rate, cm/yr
Base Roi Baudouin	2.4	40
Scott Base	1.9	11.4
South Pole	1.0	6.8

\* Corrected for radioactive decay since the time of deposition.

Pole, as section P1 offers an unambiguous stratigraphic interpretation and is not affected by the presence of the station, the  $\text{Sr}^{90}$  deposition was calculated by combining the  $\text{Sr}^{90}$  data of section HH with the yearly accumulation deduced from section P1. Because the  $\text{Sr}^{90}$  concentration is fairly constant above 1956, the uncertainty of the attributed year on section HH affected the estimate of  $\text{Sr}^{90}$  deposition very little.

There seems to be an inverse relation between

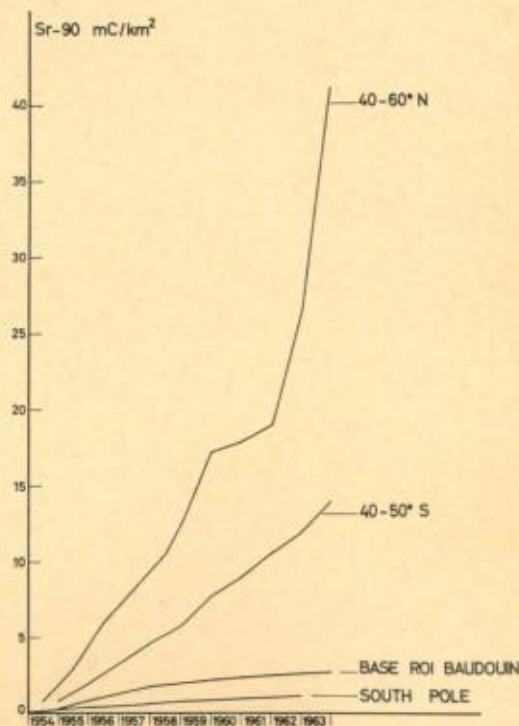


Fig. 7.  $\text{Sr}^{90}$  deposition at Base Roi Baudouin and South Pole. The data for 40-60°N and 40-50°S (compiled after Walton [1961] and HASL [1964]) are shown for comparison.



the  $\text{Sr}^{90}$  concentration in snow and the rate of water accumulation on one hand and, on the other hand, a direct relation between the total deposition and the rate of water accumulation, but the observations are too few to be conclusive.

The rate of accumulation at our sampling site near Scott Base seems to be too low in comparison with the regional value [Stuart and Bull, 1963; Heap and Rundle, 1964] because of the proximity of important mountains. On the contrary, the figure for the accumulation at Base Roi Baudouin may include a contribution of drift snow from the continental slope. According to Kotliakov [1964] 10 to 15% of the accumulated snow could be of such origin.

These different factors would be statistically compensated with a sufficient number of stations. Meanwhile, it seems reasonable to estimate that the  $\text{Sr}^{90}$  deposition over the Antarctic area up to January 1963, corrected for radioactive decay since the time of deposition, lies between 1 and 3  $\text{mc}/\text{km}^2$ .

The total  $\text{Sr}^{90}$  deposition up to January 1963, in the 70–90°S belt would be  $30 \pm 15$  kc. This amount represents about 0.2% of the total injected and 0.5% of the total fallen in January 1963 [Machta et al., 1963]. The  $\text{Sr}^{90}$  deposition per unit area in the 70–90°S belt amounts to only 5% of the deposition in the 40–60°N belt, where it attains its maximum.

Figure 7 shows the cumulative  $\text{Sr}^{90}$  deposition between 1954 and 1963 at Base Roi Baudouin and at the South Pole. For comparison we have added the cumulative deposition found in the 40–60°N and 40–50°S belts. The rates of  $\text{Sr}^{90}$  deposition are nearly constant at both Antarctic stations and are respectively about 0.2 and 0.1  $\text{mc}/\text{km}^2$  yr.

*Note added in proof.* Since this article was prepared, the note of Volchok, "Sr<sup>90</sup> fallout in Antarctica," was issued in U. S. Atomic Energy Commission's Health and Safety Laboratory Report HASL-161, p. 286, July 1, 1965. At Byrd Station, one of us (Picciotto) found a  $\text{Sr}^{90}$  deposition of 1.6  $\text{mc}/\text{km}^2$  up to February 1965. This additional information is in agreement with our conclusions.

*Acknowledgments.* Part of the equipment used in this work is the property of the association EURATOM-ULB-C.N.E.N. (contract 013-61-7

AGEC). The 1960 drilling at Base Roi Baudouin was sponsored by the contract EURATOM-C.N.E.N. 002-60-12-GEOC.

We wish to thank Mr. O. Giuliani and Mr. R. Janssens for technical assistance.

This work was carried out with the financial and logistic support of the U. S. Antarctic Research Program through National Science Foundation grants GA 93-AA 487 and GA 23-AA 422.

Financial support of the Institut Interuniversitaire des Sciences Nucléaires and the Fonds de la Recherche Scientifique Fondamentale Collective is also acknowledged.

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(Manuscript received June 12, 1965;  
revised September 9, 1965.)