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ARTIFICIAL RADIOACTIVITY REFERENCE HORIZONS IN GREENLAND FIRN

G. CROZAZ
Service de Géologie et Géochimie Nucléaires, Université Libre de Bruxelles, Belgium

C. C. LANGWAY Jr.
U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, USA

E. PICCIOTTO
Service de Géologie et Géochimie Nucléaires, Université Libre de Bruxelles, Belgium

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Total beta measurements have been made on melt water samples from a stratigraphically dated firn core profile from the inland Greenland ice sheet (77°10'N, 61°08'W). A marked increase in radioactivity is found in the 1953 firn layer which corresponds to the first important fallout from nuclear test bombs. The pre-1953 natural beta activity is 5 d.p.m./kg. The influx of artificial debris from the Ivy tests in 1953 is noted by a sharp rise in beta activity to 10 d.p.m./kg. Total ^{90}Sr deposit to June 1964 is 9.3 ± 1.5 millicuries/km^2 (24 ± 4 mC/mi^2). Average ^{210}Pb activity at time of deposit is 3.9 ± 0.4 d.p.m./kg.

1. INTRODUCTION

The determination of snow accumulation rates is a vital factor in estimating the net budget of polar ice sheets. These measurements are generally based on the stratigraphic interpretation of profiles from exposed pits or augered cores, and less frequently by direct measurements (stakes) or by the interpretation of stable isotope ratio variations (usually oxygen). These classical measuring methods, incorporate a variable amount of personal interpretation. Several investigators have discussed or demonstrated that it is possible to measure the average snow accumulation rate over the last decade by using reference levels formed by the fallout of radioactive debris from high atmospheric yield nuclear bomb tests [1-5].

The best measure of radioactive bomb debris concentration is given by the emission activity of a well defined nuclide, such as ^{90}Sr. Measurement of ^{90}Sr activity, however, requires rather elaborate chemical separation and samples of the order of several kilograms. On the other hand, measurement of the gross beta activity is a much simpler procedure requiring samples of only 10 to 100 g. In using gross beta activity measurements there are two main disadvantages:

1) the contributions of the most important natural radioactive nuclides (^{210}Pb and ^{40}K) must be taken into account, and
2) the beta activity of mixtures of nuclear bomb debris change and decay with time in a complicated and often unpredictable way.

Picciotto and Wilgain [3] have shown that in Antarctica the contributions from natural radioactive nuclides are negligible compared to artificial radioactivity concentrations. A reference horizon was found in the 1954-1955 austral summer layer [5] which appears to extend over all of inland Antarctica and corresponds to the fallout from the Castle bomb test series. This horizon is marked by a sudden increase in both the gross beta and ^{90}Sr activities.

The objective of this study is to investigate the gross beta activity in the Greenland firn layers and to determine whether artificial nuclide variations exist which could be used as accumulation reference horizons. The ^{210}Pb ac-

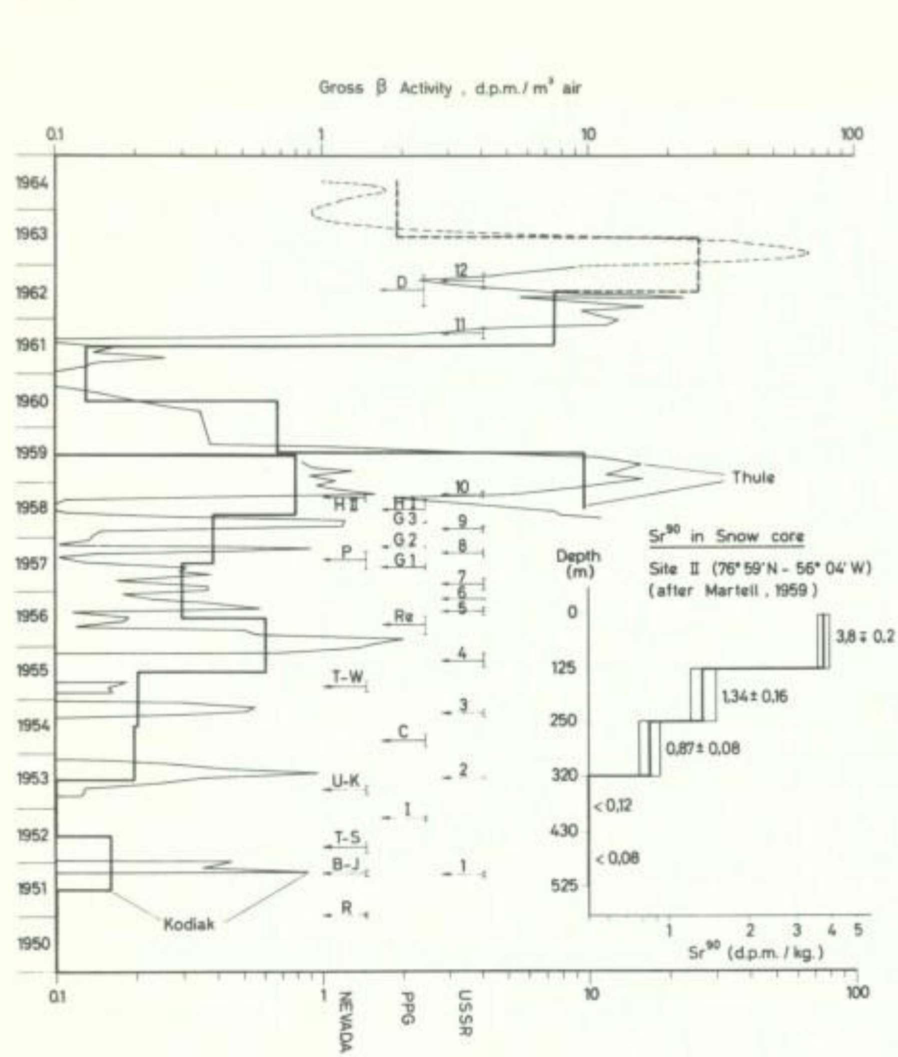

Fig. 1. (from left to right) - Gross beta activity in the air at Kodiak and Thule [8, 9]. - Chronology of the main nuclear bomb test series in the atmosphere. - Variation of ^{90}Sr activity with depth in a snow core from site II [1].

Nevada		total yield (megatons)
R	Ranger	0.040
B-J	Buster Jangle	0.072
T-S	Tumbler-Snapper	0.104
U-K	Upshot-Knothole	0.252
T-W	Teapot-Wigwam	0.197
P	Plumbbob	0.343
H_{II}	Hardtack II	0.019

Pacific proving ground (PPG)		total yield (megatons)
I	Ivy	~ 3
C	Castle	~ 53
Re	Redwing	~ 20
G_1	Grapple }	~ 6
G_2	Grapple }	
G_3	Grapple }	~ 37
H_1	Hardtack I }	
D	Dominic	37

USSR	total yield (megatons)
1	0.04
2	1
3	0.1
4	3
5 } 6	5
7 } 8	12
9 } 10	30
11	120
12	180

tivity is also measured in order to assess the contribution of the natural radioactive nuclides and to appraise the application of the ^{210}Pb dating method [6, 7] for this region of the Greenland ice sheet.

2. ARTIFICIAL ATMOSPHERIC RADIOACTIVITY IN ARCTIC REGIONS

The general evolution of artificial atmospheric radioactivity in the arctic since 1950 is known. Gross beta activity measurements of arctic air have been made from 1950 to 1960 by the U. S. Naval Research Laboratory (NRL) at Kodiak, Alaska (58°N, 152°W) and from 1958 to 1962 at Thule, Greenland (76°33'N, 68°49'W) [8, 9]. The results of these measurements are summarized in fig. 1. Activities below 0.1 d.p.m./m^3 are not recorded. The yearly averages are computed from summer to summer to allow direct comparison with our firn core measurements. The dotted curve, showing the air activity at Thule, Greenland after January 1963, is extrapolated from air measurements made at Thule after the 1958 bomb tests and from the known ratios of stratospheric injections in 1958 and 1962. Fig. 1 also contains the data of the main atmospheric nuclear bomb test series. From these data the following interpretations are made:

1) The small or large yield Soviet tests, that took place in Siberia or in Novaya-Zemlia, demonstrate a strong and immediate influence at the measuring sites, indicating tropospheric fallout.
2) The low yield (less than 1 megaton) U.S. tests carried out at the Nevada site have a weaker influence. Detection of this fallout at the measuring stations in less than 1 month also indicates a tropospheric process.
3) The high yield U.S. and U.K. tests conducted at the Pacific Ocean sites do not immediately contaminate the air at the measuring sites, indicating no tropospheric fallout.
4) The spring following high yield Soviet nuclear tests are clearly indicated in the northern latitudes air measurements.

In addition to these ground level atmospheric radioactivity measurements, important information has been published by Martell [1] on the ^{90}Sr concentrations in a well dated firn profile from site 2, Greenland (76°59'N, 56°04'W). These results are also presented in fig. 1. The ^{90}Sr activity is shown to be negligible before the summer of 1953. Thereafter the activity rises to 1 d.p.m./kg in the 1953 and 1954 snow deposits and increases rapidly to 3.8 d.p.m./kg after the 1955 summer.

3. CORE SAMPLE AND FIRN STRATIGRAPHY

The firn core used in this investigation was obtained in the vicinity of Camp Century, Greenland (77°10'N, 61°08'W) in July 1964. Camp Century is located 210 km (130 mi) east of Thule at an elevation of 1885 m (6180 ft) and, from deep bore hole measurements, has a mean annual surface air temperature of -24.6°C [10].

The 12 m deep hand augered core (7.6 cm diameter) was bored about 5 km southwest of the main camp. After recovery the core was placed on a table where light was transmitted through the core to observe subtle stratigraphic features. Density measurements were subsequently performed on the stratigraphically defined core pieces. These data are shown in fig. 2 along with the interpretations of the yearly boundaries (late summer to late summer). Average net snow accumulation for the 1947-1964 period varies from 16.4 to 49.4 g/cm^2·yr, with a mean value of 31.2 g/cm^2·yr over the 17 year profile. Independent snow stake measurements from the general Camp Century area [11] give accumulation values of 32 to 36 g/cm^2·yr for the 1961-1963 period.

After the detailed stratigraphic observations and density measurements, the external surfaces of the individual core pieces were carefully scraped and placed into pre-cleaned wide mouthed polyethylene containers. The containers were capped, allowed to melt at room temperature, and sealed with a special teflon tape. A water level line was placed on the outside of each container.

4. EXPERIMENTAL PROCEDURES

Before transfer of melt water from the containers the samples were acidified with nitric acid. The gross beta activity was measured on about 50 ml aliquot portions using a procedure similar to that described by Picciotto and Wilgain [3]. Strontium and lead carriers were also added to each original melt water container. After removing the 50 ml aliquot for beta activity measurements, all samples were combined for measurement of total ^{90}Sr and average ^{210}Pb concentrations. The experimental procedures for ^{90}Sr are described in ref. [5] and for ^{210}Pb in ref. [7].

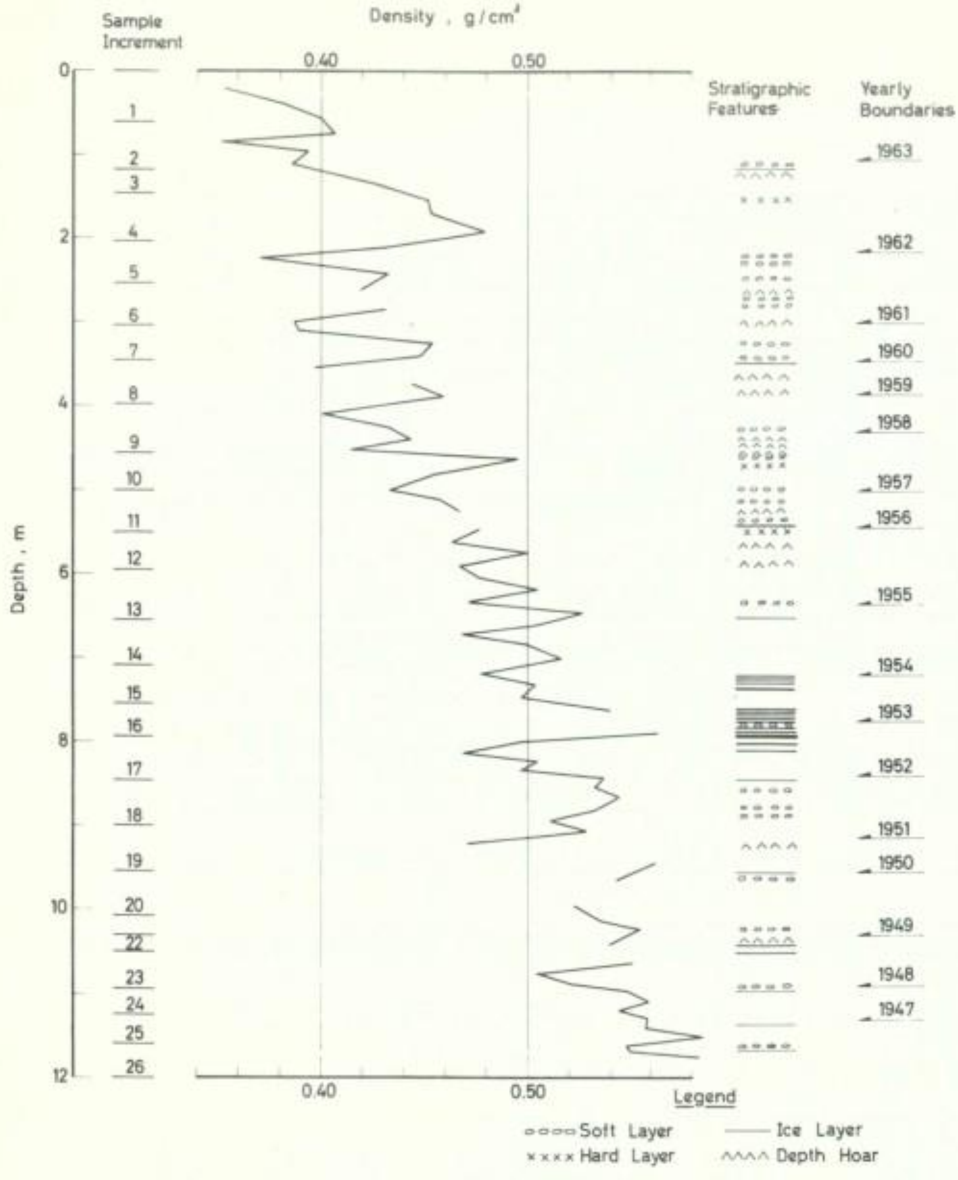

Fig. 2. Density, stratigraphic profile and yearly accumulation from the Camp Century firn core.

5. RESULTS

5.1. *Natural radioactive nuclides*

Measurements of the ionic concentrations of dissolved solids in the 1963-1964 snow accumulation layer at Camp Century show that the average potassium concentration is 0.05 mg/l [12]. This value corresponds to a ^{40}K beta activity of the order of 0.1 d.p.m./kg; which is negligible in comparison to the ^{210}Pb and other artificial beta activities.

The average ^{210}Pb activity in the 1947 to 1964 snow accumulation is 3.9 ± 0.4 d.p.m./kg with corrections applied for radioactive decay since time of deposit. The estimated error takes into account the statistical counting fluctuations, the error of the chemical yield and the uncertainty in the age of the samples. This value is appreciably higher than the 1.2 d.p.m./kg given by Goldberg [6] for the initial ^{210}Pb activity in snow samples from the South Greenland Station Crete (71°07'N, 37°19'W). It is not possible at

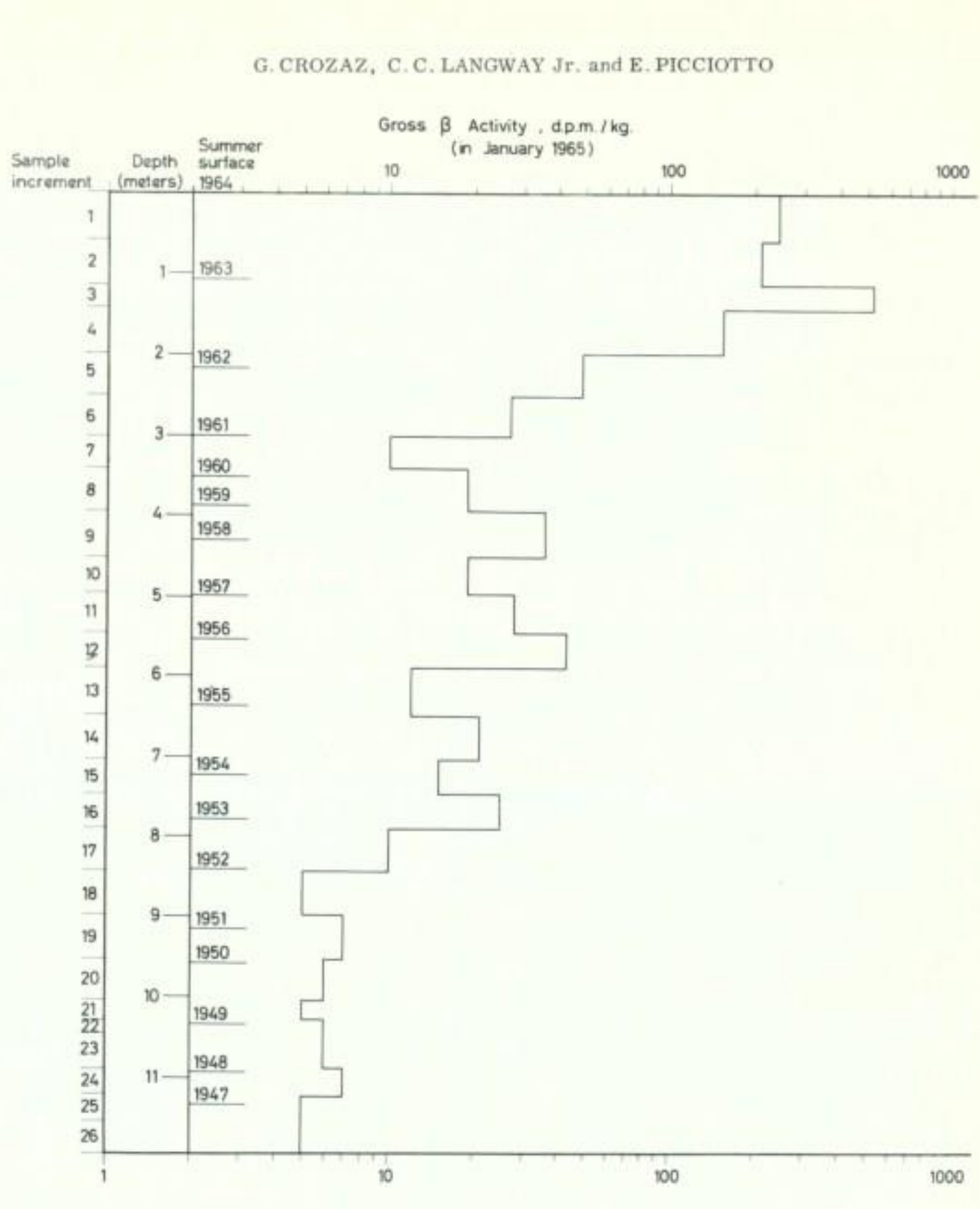

Fig. 3. Gross beta activity of snow (measured in January 1965) with respect to depth position of summer surfaces from fig. 2.

this time to determine if this difference is due only to a geographical effect.

5.2. *Gross beta activity*

The results of the distribution of gross beta activity with depth, expressed in d.p.m./kg of snow, are shown in fig. 3. The counter was arbitrarily calibrated with a potassium standard in thin layer. Taking the yearly accumulation from the stratigraphic analysis as the time standard (fig. 2), certain features are evident in the distribution of the gross beta activity over the depth profile. One observes an almost constant activity of 5.4 ± 0.5 d.p.m./kg from 1947 to 1952. A sharp rise to 10 d.p.m./kg is noted in the beta activity between the summers 1952 and 1953, followed by an irregular but steady increase to 1958. A steep decrease is noted between the summers 1959 and 1961, and finally, a second important increase is shown after the summer of 1961.

The behavior of the gross beta activity in the firn profile is in good agreement with the atmospheric data from the Naval Research Laboratory (fig. 1) and is easy to interpret on this basis. A closer agreement is not to be expected since most of the maximum peaks seen in the NRL results are due to tropospheric fallout of young products with short half-lives, most of which have completely decayed before our measurements (see for instance the peak in air activity in October-December 1951).

From 1947 to 1952, the gross beta activity in the firn layers is attributed entirely to natural radioactive nuclides, primarily ^{210}Pb and ^{210}Bi. The first increase in artificial activity shows up at 7.80 m, the spring of 1953. We are confident of the stratigraphic position of this layer because of an exceptionally good meteorological index horizon (heavy melting) at the 1954 level which is clearly marked over the north Greenland ice sheet [13]. This first noticeable increase in beta activity, therefore, must be due to the fallout of the stratospheric debris from the Ivy tests. It occurs too early to be attributed to the first Soviet thermonuclear bomb tests (August 1953).

From 1953 to 1958, the progressive increase of the activity corresponds to the almost continuous succession of high yield bomb tests. The core samples were cut too thick to show the expected seasonal fluctuations. The drop in activity during the years 1959, 1960 and 1961 corresponds to the moratorium on atmospheric nuclear bomb testing. The resumption of the tests during the fall of 1961 is clearly shown by an increase in the beta activity marking a second reference horizon. It is of interest to point out that in Antarctica the Ivy test fallout is not as prominent, and that the main radioactive reference horizon is the February 1955 firn layer resulting from the Castle tests [3]. On the Greenland ice sheet, the fallout from the Castle tests did not form a clearly marked horizon, because of atmospheric mixing of the debris with the products of the Soviet tests which had a predominant influence due to their geographical location.

To conclude the discussion of the gross beta activity measurements on the Greenland firn core we show the existence of a distinct radioactive layer, which corresponds to the spring-summer 1953 snow deposit and a second important index horizon at the 1961 level. These horizons could be very useful to glaciologists for estimating the average snow accumulation rate since 1953 over all of the Greenland ice sheet. Confirmation of these results requires additional measurements on more stratigraphically dated firn profiles from various inland locations.

5.3. *Strontium*-90 *deposition*

Since no direct ^{90}Sr measurements exist for the latitudes between 70°N and 90°N it was of interest to measure the total cumulative ^{90}Sr deposit between 1947 and July 1964 as reflected in the firn core samples. Results indicate that the cumulative ^{90}Sr deposit is 9.3 ± 1.5 mC/km^2 (24 ± 4 mC/mi^2). This value is the lowest found in the Northern Hemisphere and is compatible with the 17 mC/mi^2 value reported at Thule during the October 1959-June 1964 time interval [14].

6. SUMMARY

Melt water samples from a 12 m deep vertical firn core from Camp Century, Greenland were measured for gross beta and total ^{90}Sr content. Annual firn layers representing the time interval 1947-1964 were dated by classical stratigraphic techniques. Average net snow accumulation is 31.2 g/cm^2 · yr over the profile. An easily identifiable index horizon is found to have formed by the first important fallout of radioactive debris from nuclear test bombs. The spring 1953 firn layer is clearly marked by a sudden increase in gross beta activity which corresponds to the stratospheric fallout from the Ivy test series. The autumn 1961 firn layer will be a useful future index horizon. The gross beta activity before 1952 (measured in January 1965) is about 5 d.p.m./kg and rises above 10 d.p.m./kg in 1953 and to over 100 d.p.m./kg after 1962. The total deposition of ^{90}Sr to June 1964 is 9.3 ± 1.5 mC/km^2. The average ^{210}Pb activity at the moment of deposition is 3.9 ± 0.4 d.p.m./kg.

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