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DISTRIBUTION OF MEAN SURFACE STABLE ISOTOPES VALUES IN EAST ANTARCTICA ; OBSERVED CHANGES WITH DEPTH IN COASTAL AREA

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ABSTRACT

Mean samples of the snow accumulated during the last ten years have been collected at 48 stations distributed along a 850 km long axis in East Antarctica, starting from Dumont d'Urville towards Vostok. Up to 1000 m elevations the mean deuterium values are rather constant (- 150 ‰) ; then they decrease with various parameters (distance, elevation) and in particular with the mean annual temperatures, according to a linear relationship (δD ‰ = 6,04 T(°C) - 51) for a temperature range from - 20 to - 55°C. The observed δD ‰ - δO ‰ relationship is discussed.

Measurements along a 303 m deep core (down to the bedrock) obtained in the coastal area show very large δD changes with mean values varying between - 150 and - 360 ‰; this last value characterizes present surface snow deposited about 800 km upstream. The observed δD variations may be explained by changes in the site of origin of the ice ; mechanisms which could explain the presence of ice originating from further distances above less distant origin layers are discussed.

RESUME

Des échantillons moyens de la neige déposée au cours de la dernière dizaine d'années ont été prélevés en 48 stations réparties le long d'un profil de 850 km de long en Antarctique de l'Est, partant de la base de Dumont d'Urville en direction de Vostok. Jusqu'à une altitude de 1 000 m, les teneurs en deutérium demeurent sensiblement constantes (- 150 ‰) ; elles décroissent ensuite en fonction de différents paramètres (distance, altitude) et en particulier avec les températures moyennes suivant une loi linéaire (δD ‰ = 6,04 T(°C) - 51) entre - 20 et - 55°C. On discute la relation existant entre δD ‰ et δO ‰ .

Les teneurs en deutérium mesurées dans un carottage de 303 m de profondeur ayant atteint le socle rocheux dans la région côtière présentent de très grandes variations (- 150 à - 360 ‰), cette dernière valeur étant celle mesurée dans la neige de surface qui se dépose actuellement à 800 km en amont du site de forage. Différentes origines de la glace peuvent rendre compte des variations de δD observées ; on discute les mécanismes qui peuvent expliquer la présence de glace d'origine lointaine au dessus des couches formées à une distance moindre.

Introduction

Isotopic variations with depth in polar ice-caps are mainly connected with climatic events and the flow of ice. Information about the origin of the ice and climatic changes may in particular be obtained from the present surface distribution of mean isotopic values. This distribution is still poorly known in Antarctica and this paper will analyse geographical changes observed in a sector of East Antarctica ; these results will be used for a qualitative interpretation of measurements on a core drilled in the coastal area.

1 - Surface distribution of mean isotopic values

1-1. Sampling and measurements

Surface samples were collected during the 1971-72 and 1972-73 field seasons along a 840 km long axis starting from Dumont d'Urville towards Dome C (Fig. 1 - Table 1). The 48 sampled stations (including 7 stations previously studied) cover an elevation range up to 3 000 m with mean annual temperatures varying from - 10 to - 54°C ; they generally represent a length of time of the order of 10 years which should eliminate the influence of seasonal changes. The deuterium content is measured in δ ‰ relative to SMOW, with an accuracy of $\pm$ 0,5 ‰ . For most of the stations the mean annual temperature was measured at 10 m depth with an accuracy of the order of 1/10°C. Elevations were determined by barometric levelling with an accuracy decreasing with distance which is difficult to evaluate.

1-2. δ D ‰ - δ ^{18}O ‰ relationship

For comparison purposes the deuterium and oxygen 18 contents were measured on 18 samples (including 5 samples from Vostok kindly provided by Dr. Barkov and the SLAP standard). Results are plotted in Fig. 2

together with the δD ‰ = 8 δO ‰ + 10 relationship which is currently adopted from comparative measurements on antarctic samples (Epstein and Sharp, 1967) covering a rather narrow range which were in rather good agreement with this equation obtained from more general surveys (Craig, 1961 - Dansgaard, 1964). Although our measurements are rather close, low δD ‰ experimental results are systematically slightly higher than values calculated from the equation, the difference being of the order of 10 ‰ for δO ‰ = - 60. This should be kept in mind when comparing deuterium and oxygen 18 measurements.

1-3. Results and discussion

As expected (cf. for instance Dansgaard and others, 1973) the mean stable isotope content decreases with the increasing distance and elevation and with decreasing temperatures ; this general trend can be explained by the isotopic fractionation which takes place in the atmosphere during precipitation processes, the preferential condensation of heavier molecules leading to lower δ values for both water vapour and precipitations in air masses penetrating over Antarctica.

However the examination of the data leads us to consider two sets of values :

a - Coastal stations - For stations with an elevation of up to 1000 m elevation the δD do not decrease with elevation (Fig. 3) ; they show a rather constant value (- 150 ‰) and even suggest a slight opposite trend. It was been proposed (Dansgaard and others, 1973) that re-distribution of the snow by drift may be responsible for this but the fact that the Dumont d'Urville value was obtained from precipitations excluding snow drift (but only for a 2 year period) does not support this idea. We may also think of a possible effect of ablation (sublimation) affecting mainly the summer deposits (higher δ values) with an intensity decreasing with temperature (i. e. elevation). Another explanation would be to assume the main effect connected with orography. In this area the surface elevation reaches 1 000 m after a rather short distance (about 40 km) ; this elevation is about the level of low precipitating clouds penetrating over the continent and the surface temperature values connected with elevation changes may not be reflected in the condensation conditions, leading to rather constant δ values for precipitations as observed in temperate glaciers (Ambach and others, 1968). A compilation of antarctic data (Lorius, in press) shows that all coastal stations have rather similar δ values, and the above explanation may hold partly for Law Dome results (Budd and Morgan, 1973) the elevation effect in this area also being lower than expected.

The specific aspect of the coastal area is outlined by the accumulation distribution (Lambert and others, 1975) which reaches a maximum near the 1 000 m elevation line and by the very sharp decrease of oceanic trace elements contents (Briat and others, 1974).

b - Inland stations - The elevation effect is shown Fig. 3 ; the apparent change in the rate of the decrease of δ which is suggested around 2 300 m may be due to a "continental effect" becoming more important with marked lower slopes of the surface.

The geographical distribution of δ values is in fact influenced by many atmospheric parameters and in particular by the difference between the condensation temperature at a given location and that of the first stage of the precipitation processes (Dansgaard, 1964 ; Dansgaard and others, 1973). The temperature of condensation is not known and is tentatively replaced by the mean annual temperature (Fig. 4).

We obtain a good linear relationship :

$\underline{\delta D \text{ ‰} = 6,04\ T\ (°C) - 51}$ calculated from 36 stations ; the mean deuterium content measured at Dome C (-387 ‰ for T = - 53,5 °C) being in agreement with these results.

The representativity of the results has been checked from several near-by samples obtained in many stations, the difference between δ values never exceeding 5 ‰ ; in the central area (Dome C) a crossed network (two legs of 10 km sampled at 1 km intervals) showed a maximum scattering of 10 ‰ from the mean value. As regards the temperature, experimental errors, existence of small variations at the 10 m depth and uncertainties resulting of interpolation for some of the stations may lead to an accuracy of the order of 0,5°C.

Despite these comments systematic departures from the mean line (Fig. 4) could be connected with natural parameters ; there are, however, not enough data to study a possible effect of the variability of the snow accumulation (including snow drift); it should however be pointed out that the scattering of δ values does not increase near the coast as would be expected.

When we keep in mind the poor representativity of the mean annual temperature as regarding precipitation processes in Antarctica (Lorius, in press) the experimental relationship gives a rather good description of the δD distribution along the traverse ; the regression line also fits previous results obtained in Terre Adélie and along the Mirny-Vostok profile (Lorius and others, 1969) suggesting that the whole area is submitted to rather homogeneous conditions.

The comparison of these results with δ changes as a function of the temperature of condensation either calculated (Dansgaard, 1964) or measured in Antarctica (Aldaz and Deutsch, 1967 ; Picciotto and others, 1960) will be discussed elsewhere (Lorius, in press) with a compilation of data which shows that this relationship cannot be a priori extended to the entire continent.

2 - Isotopic changes with depth in the coastal area

2-1. Sampling

A 303 m deep hole (down to the rock base) was drilled near station D 10 (distance to the coast : 5 km ; elevation : 270 m) during the 1973-74 field season. Thermal drill equipment, operations and temperature profile (-14°C in the upper layer increasing to reach - 7°C at the bottom) are described in Gillet (in press). The δ D ‰ have been determined on discontinuous samples (10 to 20 cm thick) collected about every meter. Morainic debries were found in distinct layers in the 227 - 237 m depth interval and along the bottom 2 m.

2-2. Results and discussion

Isotopic changes with depth are shown in Fig. 5. The scattering of individual values is due to the method of sampling and decrease with depth the samples becoming more representative. From Fig. 5 and calculated 5 m means the main featuresof the curve are :

- a constant mean δ value down to about 110 m (δD ‰ = - 151)
- a δ decrease from 110 to 215 m, the change with depth being greater over the last 20 m.
- constant δ values from 215 to 245 m (- 356 ‰) and from 285 to the bottom (- 362 ‰) interrupted by a layer with much higher isotopic values (- 249 ‰ for the 260 - 280 m interval).

a - Origin of the ice

The drill hole is located approximatively along the flow line which roughly follows the traverse (Fig. 1) ; we would then expect to find with depth a continuous sequence of ice originating from increasing distances and elevations. The observed changes with depth do not contradict the picture down to a depth of about 200 meters.

The constant δ values observed in the 0 - 110 m range are in particular due to the constant δ surface value observed in this area (cf. 1-3) upstream to about 30 km from the drilling site. The δ changes with depth down to 200 m are then of the same order of magnitude as those derived from large scale flow line model calculations carried out for the Dumont d'Urville - Dome C flow line (Budd and Jenssen, personal communication). The use of such calculations is of course unrealistic in the low ice-thickness coastal areas and observed δ changes below 200 m are not in line with such models.

The origin of the ice deducted from the present surface δ distribution could be about (distances upstream from the drilling site) :

- 0 - 30 km for the 0 - 110 m depth range
- 700 -750 km for the 215- 245 m depth range
- 200 -220 km for the 260 - 280 m depth range, the origin of the ice there being similar to the one calculated at about a depth of 200 m
- 750 -800 km for the 285 - 300 m depth range. The lowest measured δ being slightly higher than the mean Dome C value.

This leads to an approximate change in the elevation of the site of formation of the order of 2700 m between surface ice and ice encountered at a depth of 215 - 245 m which is reflected in decreasing total gas content (Raynaud and Lorius, 1975).

The fact that deep ice travalled such long distances implies that it was may be formed during the last glaciation. The associated δ change measured in Vostok is of the order of δ O ‰ = 5 (Barkov and others, 1974) i. e. δD ‰ = 40 ; assuming the change was similar near the end of the traverse and that the surface profile was stable in this area, the origin of the most distant ice given above (700 - 800 km) would be lower by about 200 km.

<u>b - Possible mechanisms for the observed distribution in ice origins.</u> The discontinuous sequence of ice origins which is in particular shown by the presence of ice originating from further distances above less distant origin layers may tentatively be explained by different mechanisms :

- thermal convection (Hughes, 1972) leading to upward transport of basal ice ; according to this author conditions for convection should be most favourable in central areas but eventually convecting ice could possibly be transported downstream towards the edge of the ice sheet.

- mechanical instability in compressive flow. The existence of folding deformations in basal glacier ice debris charged layers has been discussed by Lliboutry (1965) who stated that observations may be explained by the presence of layers characterized by different viscosities. This is the case for ice with morainic debris which has small crystals with a vertical orientation (as shown from the study of a core previously obtained in the same area ; Lorius and Vallon, 1967) and very low viscosity (Duval, personal communication). A complex pattern of strain in basal ice induced by bed irregularities has been proposed (Boulton, in press) to explain the lifting up of basal debris bearing horizon to higher levels in cold glaciers. Patterns of deformation and folding in basal ice have in particular been observed as a result of compression due to obstructions to the ice flow (LeB Hooke, 1970). This is also the case in the studied coastal area of Terre Adelie as shown by the decrease in surface velocities measured downstream. The obstruction is doubtless connected with the existence of a few nunataks and the arc-shaped "ice-cored moraine" apparent on the surface is almost stagnant.

- as suggested by complex structures observed (LeB Hooke, 1970) near Thule (Greenland), folding may happen over stagnant masses which can consist of super-imposed ice but also of remains of successive advance and retreat phases of the glacier. In this last case the origins may of course be different.

Zones of shear do exist between these different ice masses ; they are characterized by very strong isotopic gradients (Fig. 5) and the existence of small crystals (Lorius and Vallon, 1967).

It may be more difficult to explain the rather constant δ values observed for instance in the 215 - 245 and 285 - 300 m depth intervals ; speculative ideas could include possible connection with complex flow patterns, the influence of progressive δ precipitation variations during the development of the last ice age which could counterbalance the δ changes expected from ice-flow models and the existence of almost constant surface δ value inland for rather large areas as suggested by Fig. 3 in the - 360 ‰ δ value range.

The distribution of the mean ice masses characterized by their isotopic content from this work and previous results (Merlivat and others, 1967 ; Lorius, 1967 ; Lorius and others, 1968) has been plotted on Fig. 6, using the ice thickness calculated from sismic and gravimetric data (Rouillon, personal communication).

Acknowledgements

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Table 1 : List of stations, distance from the coast, temperatures measured at 10 m depth, representativity (number of years covered by the sample) and deuterium content.

Station	Distance (km)	Elevation (m)	Mean Temperature (°C)	Representativity (a)	δ D %
Dumont d'Urville		40	-11,2 *	2	-153,3
A3	2,3	220	-14,5*	10	-149,9
A5	4,2	230	-15,6*	10	-154,8
D10	5,	270	-14,3*	10	-153,3
D18	11	460	-16,3 *	10	-145,5
A14	13	405	-16,1	10	-153,8
A17	16	470	-17,8	10	-148,0
D25	18,	615	-17,5 *	17	-148,5
D33	26,	730	-18,2 *	19	-142,5
A28	26,	680	-19,3	10	-149,9
A34	33,	790	-19,8	10	-146,7
D40(1)	33	850	-19,4	22	-155,4
D41	43	975	-19,8 *	17	-167,2
D43	63	1210	-22,4 *	23	-175,4
D44	73	1320	-23,3	13	-194,8
D45	83	1410	-24,0 *	25	-201,9
D47	103	1550	-25,4 *	16	-214,2
D49	123	1660	-26,9	13	-218,8
D51	143	1795	-28,2	15	-221,7
D52	153	1850	-28,8 *	15	-231,4
D54	173	1935	-29,8	22	-235,4
D57	203	2050	-32,1 *	18	-254,6
D59	223	2220	-34,3 *	10	-252,5
D61	243	2280	-36,9	9	-261,3
D62	253	2290	-37,9 *	10	-269,7
D65	283	2305	-37,6	10	-278,7
D68	313	2325	-39,5	10	-291,8
D70	333	2340	-40,4	14	-288,3
D72	353	2360	-41,2 *	39	-287,0
D74	373	2365	-41,4	13	-288,2
D77	403	2370	-41,6	11	-294,0
D80(2)	433	2430	-42,1 *	6	-300,8
D82	453	2490	-42,3	7	-295,7
D85	483	2545	-42,6 *	13	-304,9
D87	503	2580	-42,9	6	-311,3
D89	523	2630	-43,3 *	9	-319,7
D93	563	2700	-44,2	8	-332,9
D97	603	2770	-45,6 *	8	-331,5
D100	633	2810	-46,5 *	8	-330,3
D103	663	2875	-47,3	7	-332,2
D104	673	2870	-47,6	7	-353,5
D106	693	2895	-48,1	8	-342,5
D108	713	2935	-48,7 *	9	-355,8
D110	733	2960	-49,3	9	-359,3
D113	763	2990	-50,4 *	10	-367,5
D115	783	3000	-51,2	11	-359,7
D118	813	3010	-52,5	12	-353,1
D120(3)	833	3010	-53,5 *	13	-371,6

(1) 139°19'E , 66°50'S

(2) 134°49'E , 70°01'E

* = measured

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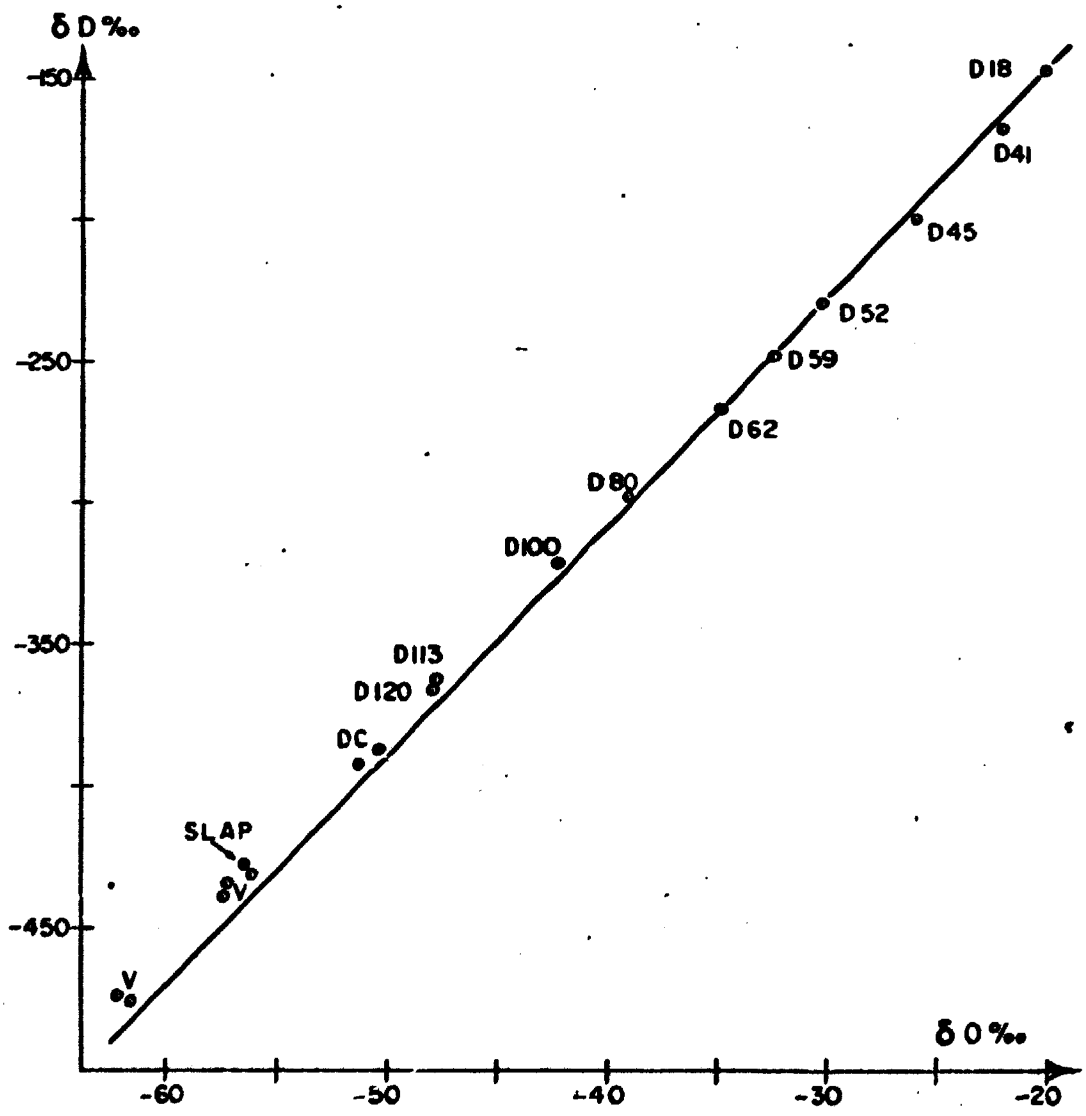

Fig. 2 - δD ‰ - $\delta^{18}O$ ‰ relationship

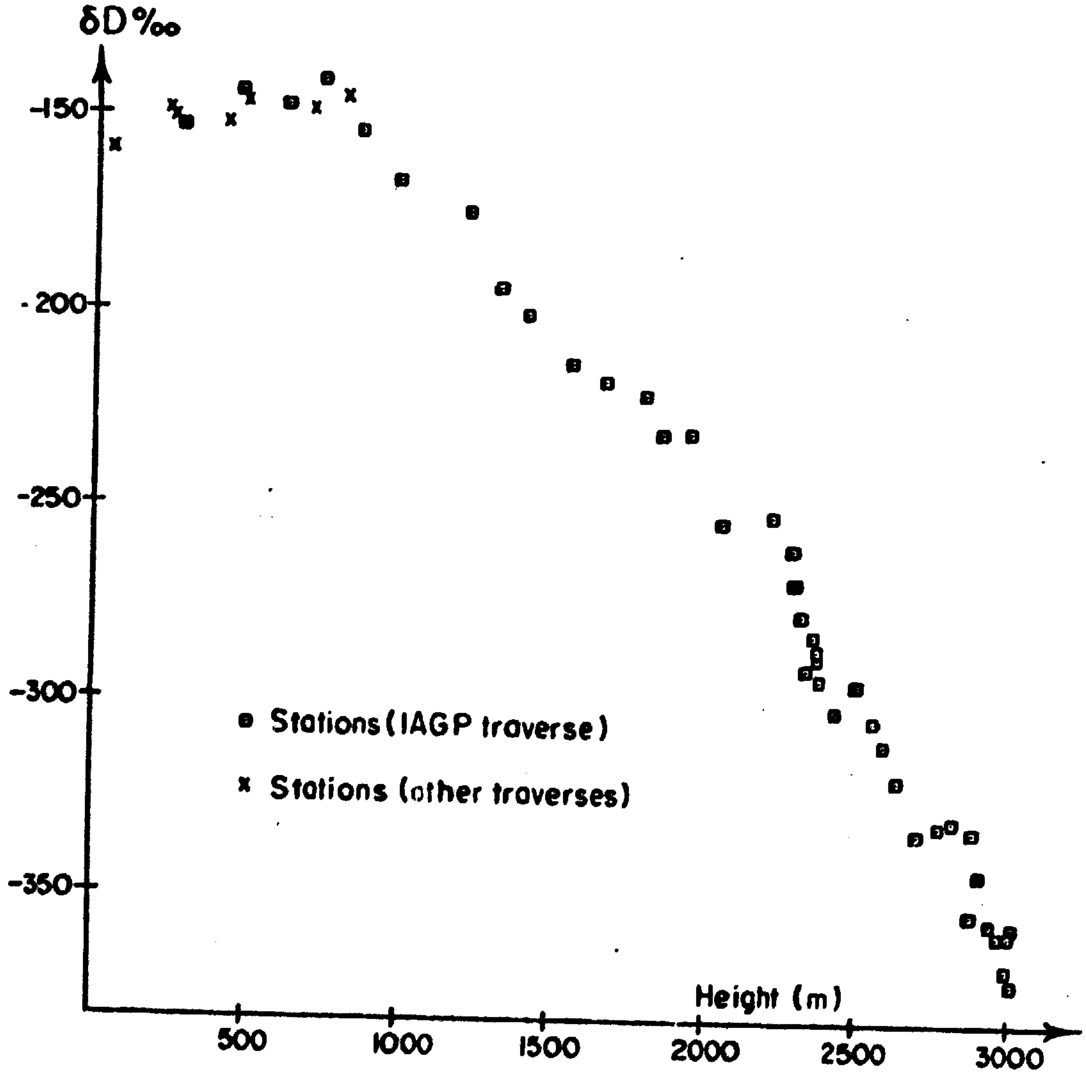

Fig. 3 - Mean deuterium content versus surface elevation

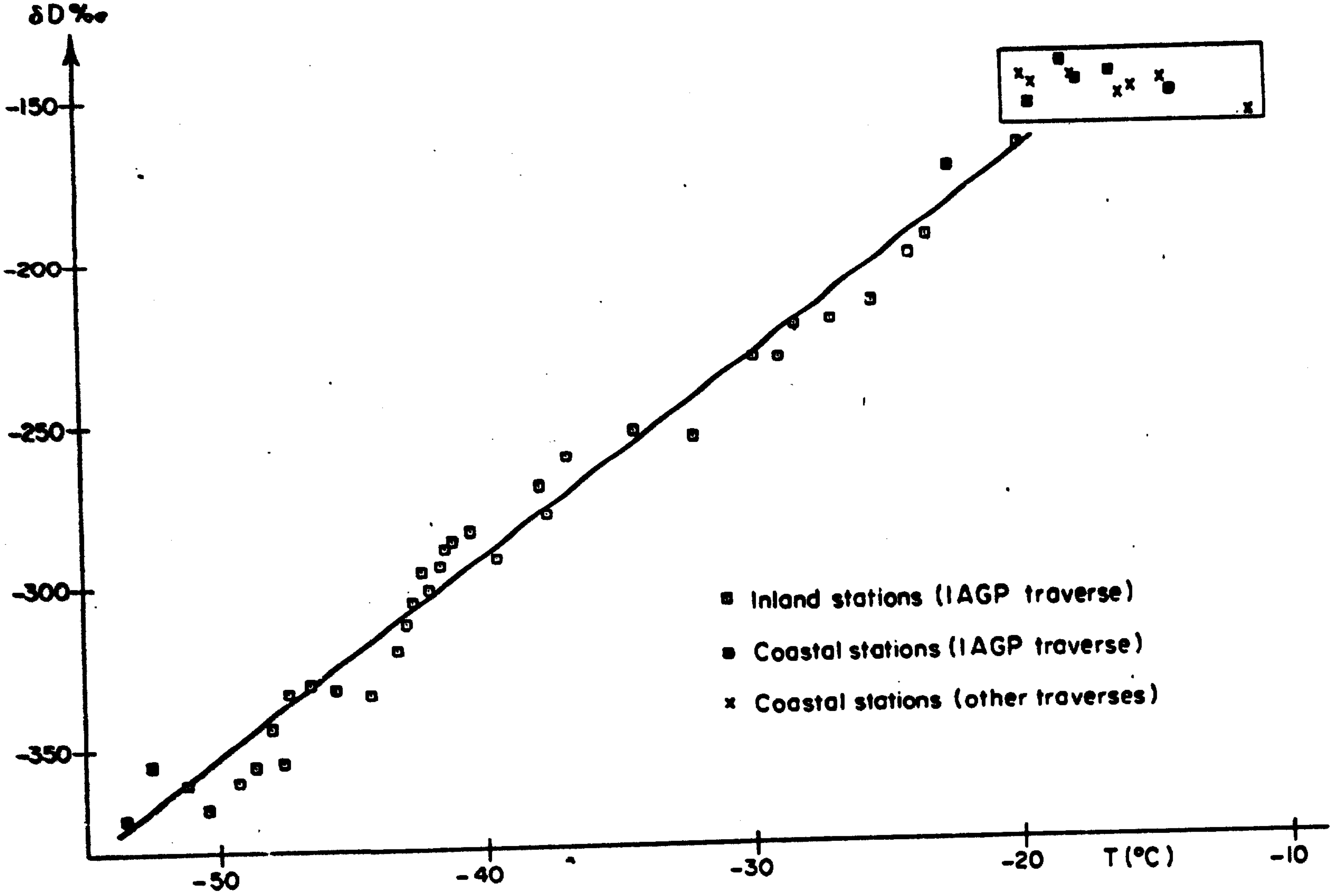

Fig. 4 - Mean deuterium content versus mean annual temperature

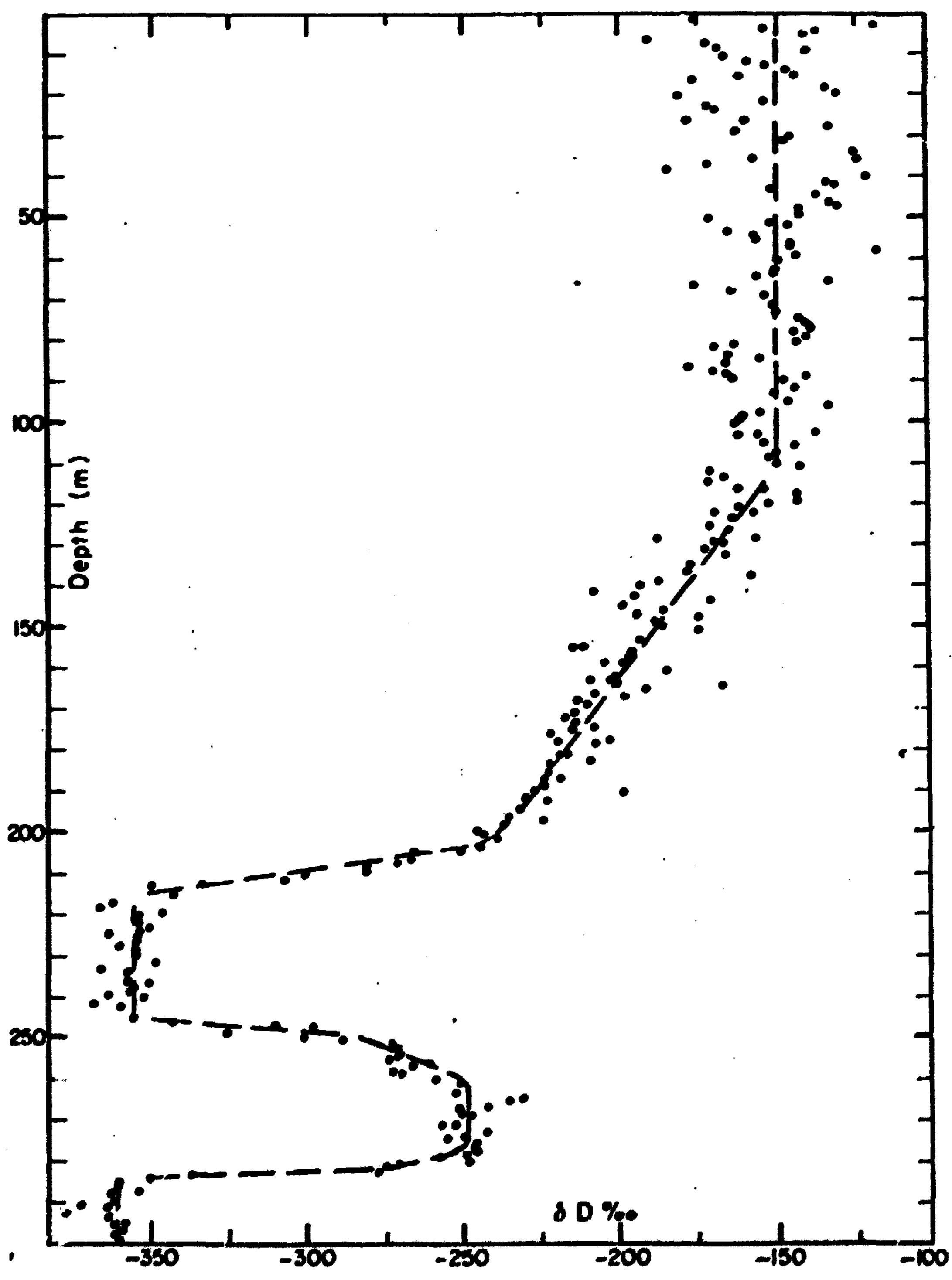

Fig. 5 - Station D 10 ; deuterium content versus depth

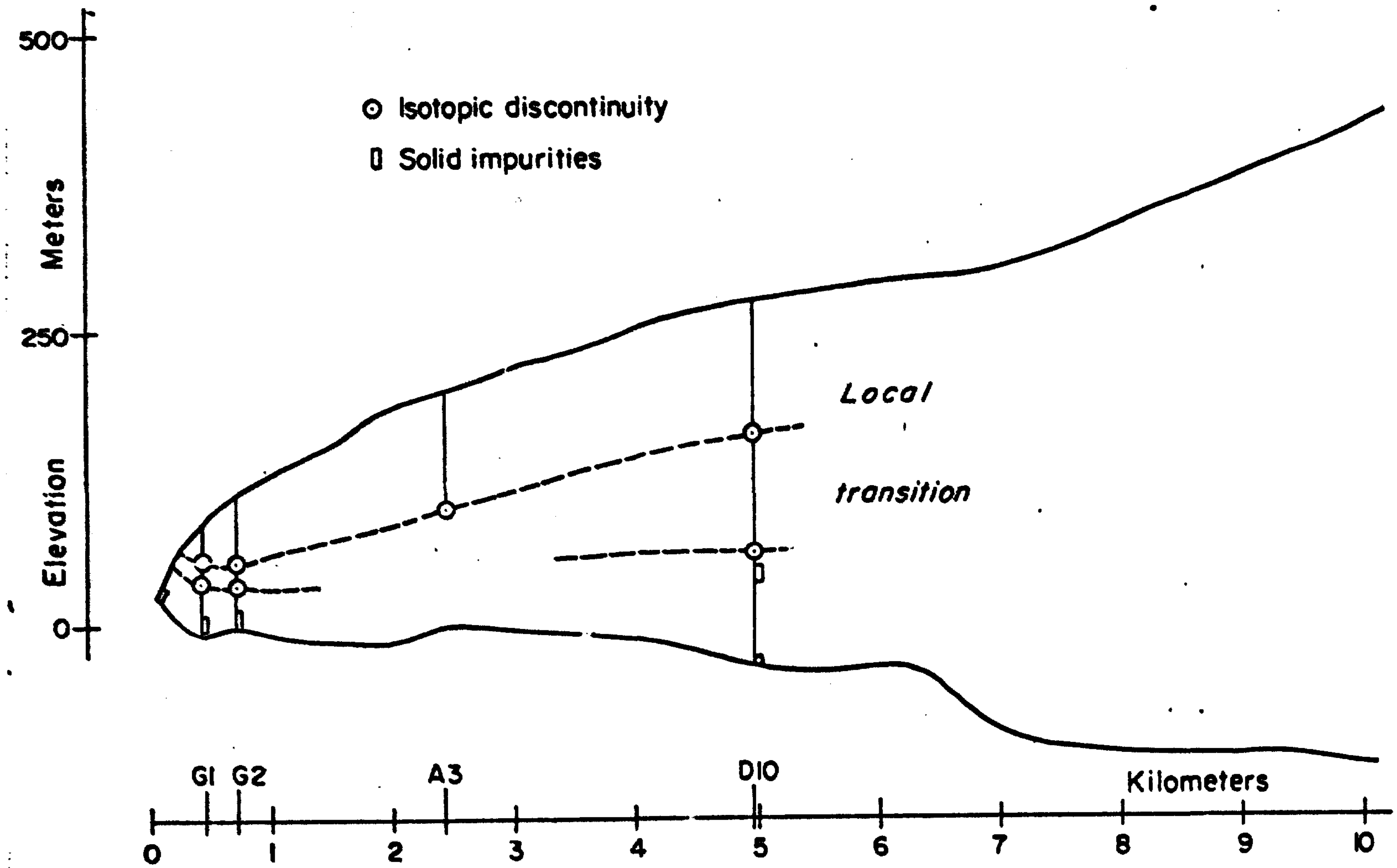

Fig. 6 - Distribution of different ice masses in the coastal area from their isotopic content