Annals of Glaciology 3 1982

STRUCTURAL STUDIES OF BARE ICE NEAR THE ALLAN HILLS, VICTORIA LAND, ANTARCTICA: A MECHANISM OF METEORITE CONCENTRATION

by

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ABSTRACT

Structural laboratory studies were made of ice collected at the surface and from a shallow bore hole in the bare ice near the Allan Hills, Victoria Land, Antarctica. The results obtained were combined with glaciological survey data to describe the mechanism of accumulation of meteorites by ice flow in a marginal area of the East Antarctic ice sheet. The age of the bare ice, approximately 20 ka, was estimated by fabric characteristics and grain size of the ice. This conforms to the minimum value of the terrestrial age of the meteorites found in the same area. The several hundred meteorite finds concentrated in the bare-ice area can be explained by an expanded catchment area during a previous ice age, or by a correction factor for the estimate of the influx rate of meteorite fall, or more probably by a combination of both.

1. INTRODUCTION

Several hundred meteorites were found during the three field seasons from 1976 to 1979 by joint US-Japanese search parties on a bare-ice area west of the Allan Hills in south Victoria Land, Antarctica (Cassidy and others 1977, Yanai 1979). In an attempt to understand the mechanism of meteorite accumulation in the area, glaciological surveys were carried out by Nishio and Annexstad during the 1978-79 and 1979-80 field seasons. They established a 13 km long triangulation chain west from the Allan Hills, details of which can be found in Nishio and Annexstad (1979, 1980). The authors reported that the vertical velocity of the ice is emergent at a rate of 0.05 m a^{-1} in the region of highest meteorite concentration. In areas closer to the main ice sheet (station west of the meteorite abundances) the ice is submerging at a rate of 0.01 - 0.03 m a^{-1}. The horizontal component of the surface velocity was measured at 2.51 m a^{-1} at stations 13 km west of the Allan Hills and decreased gradually to zero at stations nearer to the Allan Hills.

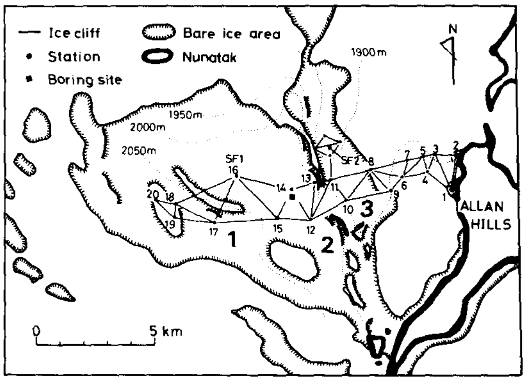

Fig.1. Reconnaissance map of the bare ice-area near the Allan Hills. Triangulation stations of the strain grid are numbered as in Nishio and Annexstad (1979). 1, 2, and 3 indicate different regions of layered ice.

In 1979, Nishio and Annexstad collected surface ice samples at station 16 and at the center of the auxiliary strain grid ABCD north of station 11. In 1980 they drilled an 8 m core near station 14 (see Fig.1). In this paper, we describe the results of the structural studies of those ice samples and estimate the age of the ice. The estimated age of the core ice roughly coincides with the minimum terrestrial residence age of meteorite falls as determined by their cosmic ray-produced radioactivity (Fireman and others 1979). A model of the accumulation process in the

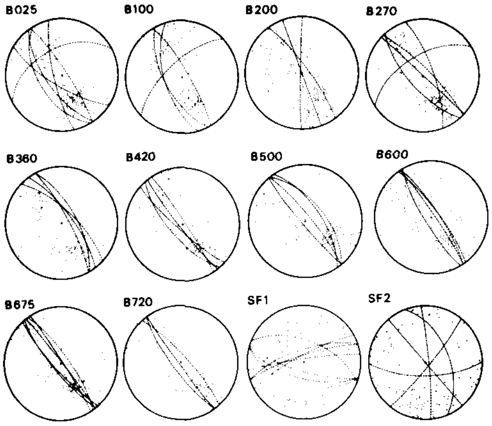

Fig.2. Fabric diagrams of ice samples obtained at surface (SF1 and SF2) and at different depths (number designates depth in cm) of shallow boring core.

area is proposed based on the age of the ice and the number of meteorite finds.

2. STRUCTURE OF THE BARE ICE

Structural elements, c-axis orientation distribution, grain size, density, and elongation of bubbles of ice samples from various locations in the bare-ice area were investigated using the universal stage in a cold laboratory. The c-axis orientation data of every specimen were plotted in equal-area stereographic projections (fabric diagrams) as shown in Figure 2. Specimens from the core are designated by the depth in cm with a symbol B, e.g. B025, B100, etc., while the surface specimens are designated SF1 and SF2 relating to the sampling sites shown in Figure 1. As can be seen in Figure 2, almost all fabric diagrams exhibit double maxima of c-axis orientation. Distributions of the c-axis orientation are rather scattered at a depth of 7.2 m and at the surface, although a slight tendency for double maxima remains. When specimens from the core are cut horizontally and inspected by transparent light, bubble lineations, as shown in Figure 3(a), can be seen. The view through

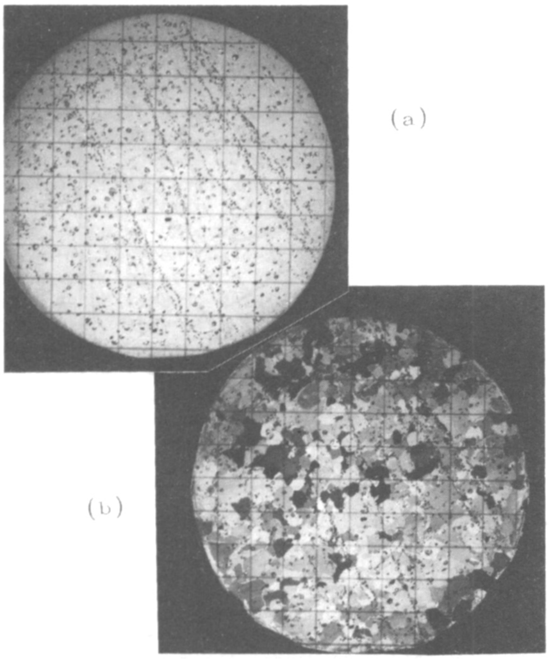

Fig.3. Horizontal thin section of ice, photographed (a) by ordinary transparent light and (b) through crossed polaroids. One division of the mesh is 1 cm.

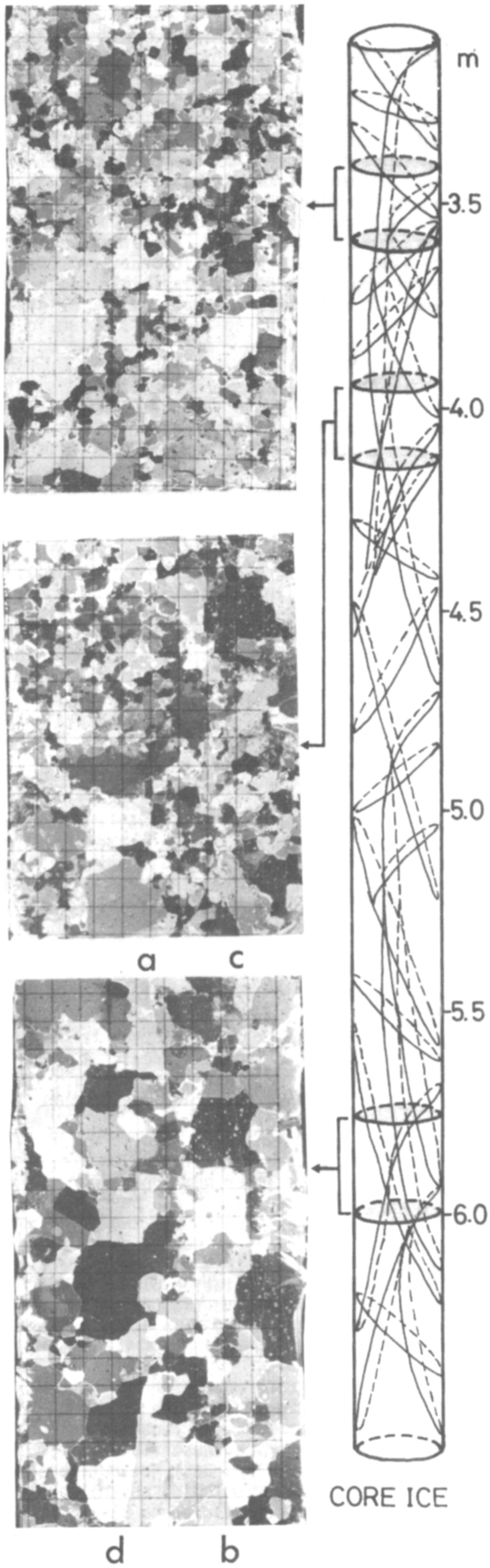

Fig.4. Vertical thin section photograph of lower parts of the core ice through crossed polaroids. Disposition of cracks approximately from 3 to 7 m depths is illustrated stereographically on the right side.

crossed polaroids of the same specimen (B200) shows a fairly homogeneous grain size of the order of 0.39 x 10^{-4} m^2 (Fig.3(b)). A thorough inspection of core samples deeper than 3.0 m were carried out before cutting specimens and dispositions of cracks in the ice are drawn stereographically by broken lines as shown in Figure 4. The bubble lineations were found to be intersects of the crack planes with a horizontal plane as that of Figure 3(a).

Average grain size of the surface specimens as well as that of specimens from different depths of the core are tabulated in Table I. The bubble-density values are also included in this table. It is surprising that the grain size increases significantly at depths below 3.6 m. Grains as large as 3 x 10^{-2} m in diameter are found in vertical thin-section specimens from 5.75 to 6.0 m depths as shown in the bottom photograph in Figure 4. It is clear that large grains are aligned along vertical cracks, designated ab, dc. It is inferred, therefore, that these larger grains could have grown up along the crack due to the release of stress in the ice body.

TABLE I. GRAIN SIZE AND BUBBLE DENSITY OF ICE SAMPLES IN THE ALLAN HILLS BARE-ICE AREA

	mean grain size (10^{-4} m^2)	bubble density (10^6 m^{-3})
SF1	0.36	95
SF2	0.20	150
B025	0.36	120
B100	0.30	110
B200	0.39	70
B270	0.36	80
B360	0.81	60
B420	0.87	59
B500	0.90	46
B600	1.40	50
B675	1.41	63
B720	1.40	52

Crack planes are drawn in the fabric diagrams of Figure 2 as projected great circles which are formed when they intersect the lower hemisphere for stereographic projection of c-axes. It can be seen from these diagrams that the direction of two principal c-axes (the double maxima) are nearly parallel to the crack planes. This implies that the crack planes are quite different from the foliation planes which should appear perpendicular to the preferred orientation of c-axes in glacier ice when it is subjected to shear stress.

3. HISTORY OF THE BARE ICE

It is difficult to determine the origin of the bare ice near the Allan Hills, because it is located on the margin of a large ice sheet flowing from the high plateau (Dome C area) of East Antarctica into the David Glacier system (including several outlet glaciers north from Mawson Glacier to David Glacier). Drewry (1980) mapped the flow lines in this part of the ice sheet and suggested a possible location for the catchment area of the ice flowing towards the Allan Hills. The catchment area, as outlined in Figure 5, is on the down-stream south-west margin of the wide stream converging on the David Glacier system. Since horizontal flow velocity is very small, in the order of 2 to 3 m a^{-1}, up-stream of the bare-ice area near the Allan Hills, the ice in the catchment area is almost stagnant. Therefore, the ice emerging near the Allan Hills must have originated from deposited snow in the accumulation zone of the marginal area. Due to the slow horizontal velocity and comparatively shallow depth of the ice (500 m), as will be shown in the next paragraph, the nourishment area is within 25 to 40 km up-stream of the boring site even though the length of the catchment area as suggested by Drewry is some 100 km.

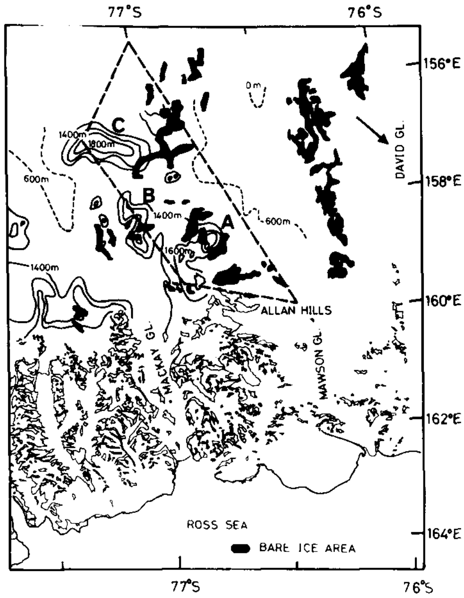

Fig.5. Map showing the catchment area (encircled by broken line) of the bare ice. Bedrock topography is illustrated by contours a.s.l. (after Drewry 1980) and the distribution of the bare ice area is identified from Landsat imagery.

Matsuda (unpublished) presented an empirical diagram (temperature vs depth) in which regions of different patterns of ice fabric (single maximum, double maxima, diamond, girdle, etc.) are divided as shown in Figure 6. The diagram is deduced from many ice-fabric data of core samples taken at various

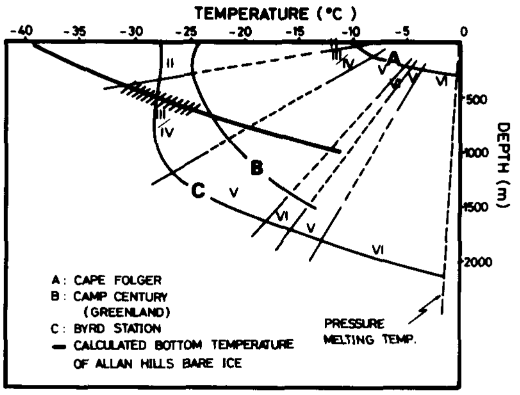

Fig.6. Diagram (temperature vs depth) in which characteristic fabric patterns of ice are divided in radial regions. Numbers of regions correspond to following characteristics: II, depositional scattered; III/IV, double maxima on small girdle; V, single maximum; VI, diamond (multi-maxima). Lines A, B, and C represent the temperature-depth profiles in ice sheets at Cape Folger, Camp Century, and Byrd station respectively. (After Matsuda (unpublished).)

sites in Antarctica and Greenland. According to this diagram, the double maxima generally found in the present study should be formed in depositional ice at a depth between 500 and 1 000 m in the temperature range between -20°C and -30°C. Nishio (unpublished) calculated possible temperature profiles in the bare ice using various hypothetical depths of the bottom and a constant surface temperature (-40°C). The relationship between bottom temperatures and the depths is shown by a bold solid line in Figure 6. If we assume that this result is applicable to the adjacent accumulation area and the double maxima are not destroyed in the uplifting process of the ice, the bottom depth which conforms with the double maxima region in Matsuda's diagram is approximately 500 m. This depth coincides roughly with the depth of the bedrock in the area approximately 25 km up-stream from the meteorite site (Fig.5). Therefore, it can be inferred from the character of the fabric pattern that the core ice and SF1 surface ice collected at the upper part of the bare-ice area should have been formed in a comparatively small basin on or near the subglacial peaks designated A in Figure 5.

There is no direct measurement of the accumulation rate in the Allan Hills catchment area and the data at the area along the Transantarctic Mountains exhibit much variety. If we adopt a mean value of 40 kg m^{-2} a^{-1}, as suggested by Drewry (personal communication), approximately 12.5 ka are needed to accumulate the ice of 500 m thickness in the catchment area. Since the horizontal velocity of the flow of ice can be presumed to be of the order of 2 to 3 m a^{-1} in the accumulation zone up-stream, the ice moves horizontally only 25 to 40 km in this time. This distance roughly coincides with that between the bare-ice area and the subglacial peaks designated A in Figure 5. Therefore we can presume that the origin of the bare ice is snow deposited in a small basin near the subglacial peaks in area A approximately 10^4 a before reaching the bottom.

The upward velocity measured at stations near the boring site is approximately 0.05 m a^{-1}, hence the emergence of ice from a depth of 500 m takes another 10 ka before it appears at the surface. In the emergent area near station 14, the horizontal velocity is approximately 1 m a^{-1} which can be considered representative for the horizontal velocity of the uplifting ice. Therefore, the horizontal movement of uplifted ice in 10 ka should not exceed 10 km. This distance is approximately equal to the extent of the bare ice as shown in Figure 1. Then the age of the bare ice should be 12.5 + 10 ≈ 20 ka.

If the grain growth rate of depositional ice is assumed to be approximately 5 x 10^{-3} mm^2 a^{-1} at -32°C as deduced from Byrd and Dome C cores (Gow and Williamson 1976, Duval and Lorius 1980), it will take about 20 ka to attain the grain size of approximately 100 mm^2 which we observe at depths below 3.6 m. In Figure 6 it is seen that -32°C is the mean temperature between the surface and 500 m depth in the area (Nishio unpublished). This value of the age of ice compares favorably with the age estimated by the accumulation described in the previous paragraph and it implies that we are observing ice in the Allan Hills formed by precipitation during the last ice age.

4. DISCUSSION

The age of the bare ice at the boring site is estimated to be of the order of 20 ka using accumulation and uplift rates of the ice in a marginal catchment area near the Allan Hills. This compares favorably with an age calculated from the growth rate of grains in ice samples collected in the same area.

Based on the estimated age of 20 ka of ice in the area and its inferred origin near the subglacial peaks, a model for meteorite accumulation has been constructed. It is assumed that the meteorites fell in the nourishing area around the subglacial peaks, A in Figure 5, during a period between 20 and 100 ka BP. The falls were transported in submerged ice with a very small horizontal velocity along the marginal area of a large ice sheet, and emerged in a stagnant area produced by the barrier effect of the Allan Hills. The terrestrial age of meteorites found in this area is more than 30 ka with a maximum frequency (in 19 samples) between 30 and 100 ka (Honda 1979). The maximum terrestrial age of meteorites could be an indicator of the time when the ice sheet covering the Allan Hills began to recede and became stagnant.

The comparatively small catchment area (5 x 10^2 km^2) east of the subglacial peaks A seems to be of insufficient size to supply the several hundred meteorites found in the area. If the influx rate of meteorite falls on the Earth's surface is taken to be 1 x 10^{-6} km^{-2} a^{-1} as shown by Millard (1963), only 40 specimens would accumulate in a period of 80 ka (between 20 and 100 ka BP). This is much less (more than one order of magnitude) than those actually collected at the Allan Hills meteorite site. If we assume that the catchment area of the ice flowing to the meteorite site was larger during the most active period of the last ice age, we could expect a greater influx of specimens near the Allan Hills.

The surface topography, as shown in Figure 2 of Nishio and Annexstad's paper (1980), indicates that the ice body near the Allan Hills is composed of three different parts. The direction of flow, almost eastward, of the ice in the lowest layer (below 1 950 m) seems to indicate that the direction of the velocity vector is similar now to what it was when the ice flowed over the Allan Hills. In the next higher layer, between 1 950 and 1 050 m, the flow direction deviates 10° toward the north from the lowest layer. The top layer, higher than 2 050 m, has almost the same direction of flow as that of the main ice stream at the present time. Such layer structure, with different directions of flow, indicates that the lowest layer may be remnant ice which once flowed over the Allan Hills when the ice sheet was thicker. The thicker ice sheet which flowed eastward during the last ice age should have had a much wider catchment area, probably 10 times or more, than the whole area indicated by the dashed lines in Figure 5. Therefore, meteorites which fell in this wider area during the last ice age are still emerging in the lowest part of the bare ice field.

Another explanation for the larger number of meteorites actually found can be given by using the correction factor for the influx rate proposed by Millard (1963). The correction factor is 14 and the final influx rate he proposed is 1.5 x 10^{-5} km^{-2} a^{-1} giving an estimated value of 600 which is close to the observed number of finds. Conversely, if we can determine the area of collection of meteorites precisely for any meteorite site on the Antarctic ice sheet, the validity of the correction factor could be verified.

The existence of very large grains along cracks in the deeper part (below 3.6 m) of the core ice can be explained by recrystallization along the cracks due to the release of stress generated in the ice. Formation of cracks as deep as 8 m can be explained by thermal contraction of ice due to the annual variation of surface temperatures which can be as high as 60°C. The fact that c-axis orientations of these large grains appear separated from the concentrated poles of double maxima on the fabric diagram could be a proof of the recrystallization mechanism. However, it is difficult to explain why those large grains appear at depths below 3.6 m.

An alternative mechanism for the formation of large grains along cracks can be explained by submergent flow observed up-stream of the bare-ice area. When the ice emerged on the surface, probably it became cracked and was submerged again when covered by snow of a certain thickness due to local movement of the firn line over a comparatively long period. The ice reappeared at the surface after flow during which grain growth had continued. This process of superficial flow over a distance of several kilometers can be formulated using the data of ablation, vertical velocity, and surface dilatation obtained from the strain grid data. However, this process can be only suggested at present because errors of the strain grid measurements over the interval of 1 a are as large as 100%.

5. CONCLUDING REMARKS

Structural studies of the ice collected at the bare-ice area near the Allan Hills reveal that its age is more than 20 ka which conforms to the minimum terrestrial age of meteorites collected at the same area. The meteorites fell in the marginal area of the ice sheet which flows into the David Glacier system during the period between 20 and 100 ka BP. Continued emergence of the ice in the bare-ice area near the Allan Hills has resulted in an accumulation of meteorites transported in the ice. The number of meteorites found in this area coincide with the expected number calculated from a corrected influx rate and an expanded catchment area.

It is desirable to extend the measurements of the strain grid in the area for a long period of time to obtain more accurate data on the flow pattern of the ice. It is also desirable to know the bedrock profile as well as to collect more ice samples from various sites. In addition, more data on the terrestrial ages of meteorites found would add to the body of knowledge about the mechanism of concentration of meteorites in bare-ice areas of Antarctica.

ACKNOWLEDGEMENTS

The field work of this study was supported by grants from the US National Science Foundation and the National Institute of Polar Research, Japan. Laboratory work was mostly carried out in Hokkaido University. The authors would like to thank Dr M Nakawo of the Faculty of Engineering, Hokkaido University, for valuable discussions.

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