STUDIES ON THE ICE FLOW IN THE BARE ICE AREA NEAR THE ALLAN HILLS IN VICTORIA LAND, ANTARCTICA

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***Abstract*:** The mechanism of accumulation of a large number of meteorites in the bare ice area near the Allan Hills in South Victoria Land has been investigated by surveying a triangulation chain of 20 stations, 15 km in total length, during the 1978–79 and 1979–80 field seasons. The horizontal and vertical components of surface velocities of the ice sheet in the bare ice area at 18 stations and the parameters of surface strains at 18 triangles of the chain were obtained.

The horizontal velocity of the ice sheet at the station farthest from the datum point is 2.51 m/year and the velocity vector principally points in a northeast direction which is perpendicular to the contour lines. The magnitude of horizontal velocities gradually decreases from a maximum at station 20 to nearly zero at the stations near the Allan Hills. The vertical movements of the bare ice are emergent at a rate of 4.5 cm/year on the average in the region of high meteorite accumulation, while in the area of the further inland the vertical ice flow shows small submergence velocities. Ablation rates are ranging from 4.2 to 7.0 cm/year with an average of 5.7 cm/year and are balanced on the average by the emergent velocity of the ice in the meteorite accumulation area. Compressive strains are predominant in most of the triangle areas and the horizontal dilatation of each triangle area is negative (horizontal convergence).

These characters of ice flow are favorable for accumulation of a large number of meteorites on the bare ice surface in a small area, and also support a proposed hypothesis by NAGATA (1978) on the mechanism of concentration of Yamato meteorites within the Meteorite Ice Field near the Yamato Mountains in East Queen Maud Land, where the triangulation survey has also shown an upward flow of ice.

1. Introduction

About 650 meteorite specimens were found and collected on the bare ice surface west of the Allan Hills in South Victoria Land during the last four field seasons since the 1976–77 season by a joint U. S.-Japan meteorite search team (CASSIDY *et al.*, 1977; SHIRAISHI, 1979; YANAI, 1979). To clarify the mechanism of accumulation of a large number of meteorites within the limited bare ice area of the Allan Hills, it was planned to study flow patterns of ice in this area of bare ice.

In December 1978, a 15 km long triangulation chain composed of 20 stations, forming a series of 18 triangles, was newly established in the Allan Hills bare ice field. And then the positions and elevations of all the triangulation stations were determined by triangulation survey (NISHIO and ANNEXSTAD, 1979). The resurvey of the chain was carried out by the method of the triangulation survey in December 1979 one year later. Other glaciological elements were also measured along the triangulation chain; the ice thickness was measured by a portable radio echo sounder (KOVACS, 1980), ablation rates were measured with the stakes of the chain, and the surface slope at each triangulation station was determined by a theodolite reading the vertical angle of the horizon at twelve directions.

In the present paper, the reduced data such as the horizontal and vertical velocities of surface flow, parameters of surface strains and ablation rates in the bare ice area are presented. The distributions of the velocities and ablation rates on the bare ice surface are discussed in conjunction with the surface morphology. It is confirmed that the proposed hypothesis (NAGATA, 1978) on the mechanism of concentration of Yamato meteorites in a very limited area is applicable to the meteorites occurrence in the area around the Allan Hills.

2. Calculation of Surface Flow Vectors and Strains

2.1. *Horizontal surface velocity*

The horizontal velocity vector of ice movement at each triangulation station was calculated from the difference in the two cartesian coordinates (X, Y) between December 1978 and December 1979, where the coordinate origin was taken at the datum point on the bedrock of the Allan Hills, and the direction of X coordinate is geographical north and that of Y is east. The horizontal displacement ΔS and its direction α indicated by the azimuth clockwise from the north are given:

$$\Delta S=\sqrt{(\Delta X)^2+(\Delta Y)^2} \tag{1}$$

$$\alpha=\tan^{-1}(\Delta Y/\Delta X) \tag{2}$$

where ΔX and ΔY are the difference in the cartesian coordinates of X and Y, respectively. Therefore, the horizontal surface velocity per year at a station is obtained by

$$V_h=\Delta S\cdot 365/N \tag{3}$$

where N is the number of days between two observations, ranging from 352 to 377 days.

Table 1 shows calculated values of V_h (m/year) and α (degree) at 18 surveyed stations, together with each station's latitude, longitude, elevation, ice thickness,

Table 1. Geodetic position, elevation, ice thickness, surface velocity components and ablation.

Station	Position in December 1979		Elevation[2] (m)	Ice[3] thickness (m)	Horizontal velocity (m/year)		Azimuth of[4] velocity α (degree)	Emergence (+) or submergence (−) velocity V_v (cm/year)	Ablation (−) (cm/year)
	Latitude[1] (S)	Longitude[1] (E)			V_h	error			
1	76° 42′ 12″	159° 31′ 47″	2054						
2	76 41 23	159 32 28	1910						
3	76 41 23	159 30 20	1946	130	0.07	±0.11	68	−0.6	−2.3
4	76 41 45	159 29 36	1956		0.06	±0.10	112	−0.6	−2.3
5	76 41 26	159 29 19	1953	128	0.10	±0.11	145	−0.8	−1.1
6	76 41 52	159 27 15	1954		0.20	±0.18	80	+1.9	−1.6
7	76 41 29	159 27 50	1952	310	0.17	±0.16	123	−1.2	−2.5
8	76 41 40	159 24 18	1947	300(?)	0.50	±0.33	98	+1.4	−3.7
9	76 42 10	159 26 13	1949		0.30	±0.23	71	+4.6	−4.2
10	76 42 21	159 21 52	1945		0.80	±0.48	71	+6.7	−6.5
11	76 41 54	159 20 21	1945		1.00	±0.56	81	+7.1	−5.6
12	76 42 48	159 18 25	2031		1.23	±0.67	61	−1.7	−4.5
13	76 42 02	159 18 07	2008		1.29	±0.69	75	+6.5	−5.6
14	76 42 07	159 16 33	2014		1.21	±0.78	72	+0.8	−7.0
15	76 42 46	159 15 12	2047		1.40	±0.84	60	−2.7	−5.7
16	76 41 50	159 11 20	2022		1.82	±1.07	76	−1.2	−4.2
17	76 42 51	159 09 09	2075		2.02	±1.14	54	−1.0	−5.1
18	76 42 26	159 05 40	2068		2.37	±1.30	56	−1.0	−4.5
19	76 42 45	159 05 27	2075		2.34	±1.31	54	−3.5	−3.1
20	76 42 21	159 03 36	2071		2.51	±1.33	55	−2.5	−1.8

Notes [1]Latitude and longitude: Geodetic position of each triangulation station in December 1979.
[2]Elevation: Elevation (a.s.l) of each triangulation station in December 1979.
[3]Ice thickness: Radio echo sounding was carried out along the triangulation chain (Stations No. 2, 3, 5, 7, 8 and 11) in December 1978 (Kovacs, 1980).
[4]Azimuth of velocity (α): Direction of the horizontal velocity indicated clockwise from the geographical north.

vertical velocity and ablation rate. The horizontal surface velocity V_h adopted here does not refer to the surface of the ice sheet in the bare ice area, but to the cartesian coordinates centered at the datum point on the mean sea level. The difference of the velocities due to the elevation is negligible, being calculated as 0.03% of the value of the surface of the ice sheet, 2000 m in elevation.

Mean square errors in cartesian coordinate were calculated at each triangulation station, separately in the first survey of 1978 and the second survey of 1979. Therefore, mean square errors in the horizontal surface velocity V_h and its azimuth α can be computed by applying the theory of propagation of error to eqs. (1), (2) and (3). The maximum error in position was obtained at Station No. 20 (all station numbers are given in Fig. 2 of NISHIO and ANNEXSTAD, 1979) which was the farthest station from the datum point, where the mean square error in position was 1.46 m in the first survey and 1.09 m in the second survey; consequently, absolute value of the error in horizontal surface velocity V_h and azimuth α at Station No. 20 were $\pm$ 1.33 m/year and ± 10 degrees respectively. The absolute value of errors in V_h showed gradual decrease from Station No. 20 towards the datum point, but the absolute values of error in V_h at Stations No. 3, 4 and 5 were larger than the values of calculated horizontal surface velocity because of small movements of these stations.

On the contrary, errors in azimuth were almost constant in a range from 10 to 15 degrees at all the triangulation stations. As the result, the errors in the horizontal surface velocity V_h showed relatively large values such as 53 to 94% of V_h in relative error since the ice flow in the bare ice area near the Allan Hills was relatively slow and the time interval of one year between two observations was short.

2.2. *Emergence or submergence velocity*

The surface elevations of triangulation stations with reference to the datum point, taken as 2054.00 m above sea level, in December 1978 and December 1979 were calculated.

Fig. 1 shows schematically the movement of a surveyed stake from 1978 to 1979 in the ablation area with an emergence flow which occurred actually in the Allan Hills bare ice area. As illustrated in Fig. 1, the vertical displacement ΔH of the top of a stake was obtained by subtracting the thickness of ablation of ice (B in Fig. 1) from the above two surface elevations. The vertical velocity V_v of the ice flow was given as the emergence velocity or submergence velocity by taking into account the surface slope θ_s. The horizontal displacement ΔS and the vertical displacement ΔH of the surveyed stake were measured with respect to the coordinates fixed on the datum point. If the ice flows parallel to the surface, ΔH would be equal to $\Delta S \cdot \tan \theta_s$. However, since the flow of ice in the bare ice area is supposed to have upward component V, the observed vertical displacement ΔH is less than $\Delta S \cdot \tan \theta_s$ by an amount of V. V should be equal to the surface rise if there is no surface ablation. Therefore, the vertical velocity V_v is given as follows:

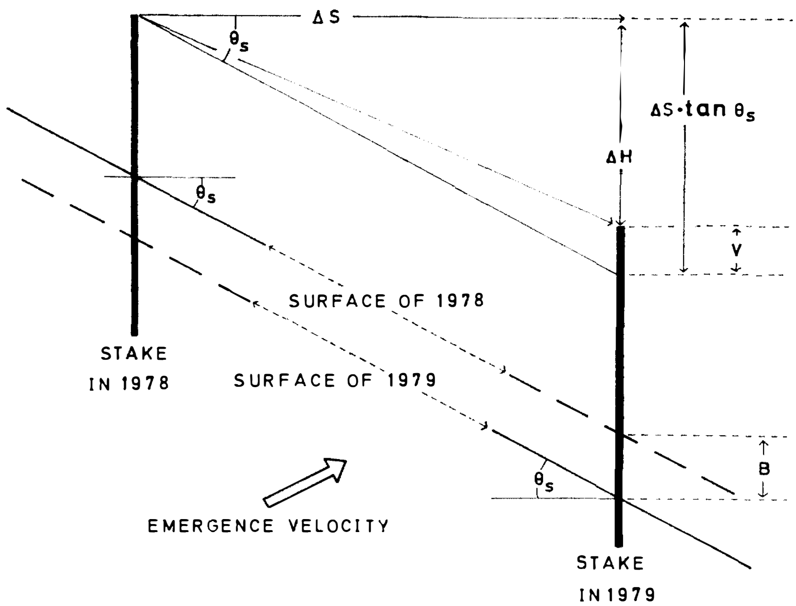

Fig. 1. A schematic diagram showing the movement of a survey stake in the ablation area with an emergent flow in the period from December 1978 to December 1979.
ΔS: Horizontal displacement during the period,
ΔH: Vertical displacement during the period,
V: Emergence or submergence of the stake in a year,
B: Ablation of ice surface,
θ_s: Surface slope along the ice flow direction.
The sign of ΔH, V, B, and θ_s are measured positive upward.

$$V_v = V_h \cdot \tan\theta_s + \Delta H \cdot 365/N \tag{4}$$

where ΔH, V_v and θ_s are taken positive for upward flow in Fig. 1. Calculated vertical velocities are also shown in Table 1.

The mean square error involved in the vertical velocity V_v which was calculated from eq. (4) was obtained at each station, assuming the error of 10 minutes in the surface slope θ_s.

The relative error in the vertical velocity thus obtained was as large as 100% in the inland region around Stations No. 15, 17, 18 and 20, whereas the errors were smaller as 85% in the area of highly accumulated meteorites around Stations No. 9, 10, 11 and 13.

2.3. *Surface deformation in the bare ice area*

Assuming that the surface strain was homogeneous in each triangle of the chain in the Allan Hills bare ice field, the surface deformation was obtained for each triangle.

To find the surface strain rate, the JAEGER's method (1969) was used as the rate of deformation of a circumscribed circle of an unstrained triangle into a strain ellipse caused by a homogeneous strain. Geodetic coordinates of three points of each triangle along the triangulation chain were obtained both in 1978 and 1979, hence, the shape of the strain ellipse and the rotation of the principal axis of the strain can be calculated. Taking the radius of the circumscribed circle of an initial triangle as the unity, and the lengths of major and minor axis of the strain ellipse as A and B respectively, the parameters of the ice deformation such as principal strain rate, surface dilatation, maximum shear strain rate and rotation of principal axis of the strain are computed as a function of A and B. As the result of calculation of the values of A and B of each triangle along the chain, the following strain parameters were obtained for 18 triangles:

α: Azimuth clockwise from north of the principal axis of the strain ε_1.

$\dot{\varepsilon}_1, \dot{\varepsilon}_2$: Principal strain rate per year, calculated from $\dot{\varepsilon}_1 = A-1$ and $\dot{\varepsilon}_2 = B-1$. The positive sign indicates the tensile strain rate and the negative for compressive. The principal strain rate of $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ respectively the algebraically maximum and minimum values among the strains in the whole directions.

$\dot{\Delta}$: Rate of surface dilatation in the area of a triangle per year, calculated from $\dot{\Delta} = AB-1$.

$\dot{\gamma}_{max}$: Maximum shear strain rate per year, calculated from $\dot{\gamma}_{max} = (A^2 - B^2)/2AB$. Its direction is $\alpha \pm 45°$.

$\dot{\omega}$: Rate of counterclockwise rotation of the principal axis of the strain per year.

Table 2. Calculated strain parameters of triangles in the triangulation chain.

Triangles	α (degrees)	$\dot{\varepsilon}_1 \times 10^{-4}$ (year^{-1})	$\dot{\varepsilon}_2 \times 10^{-4}$ (year^{-1})	$\dot{\Delta} \times 10^{-4}$ (year^{-1})	$\dot{\gamma}_{max} \times 10^{-4}$ (year^{-1})	$\dot{\omega}$ (deg·year^{-1})
1· 2· 3	7.34	+0.04	−0.68	−0.63	0.72	+0.001
2· 3· 4	357.24	+0.79	−0.66	+0.12	1.45	+0.002
3· 4· 5	39.15	+1.10	−1.56	−0.45	2.66	−0.007
4· 5· 6	27.83	−0.94	−1.59	−2.53	0.66	0
5· 6· 7	8.43	−1.35	−2.01	−3.36	0.66	−0.002
6· 7· 8	338.40	−1.86	−2.40	−4.26	0.53	−0.001
7· 8· 9	343.68	−1.59	−2.43	−4.02	0.84	0
8· 9·10	26.69	−2.17	−2.65	−4.82	0.49	+0.001
9·10·11	357.52	−1.63	−2.68	−4.31	1.04	+0.003
10·11·12	16.23	−1.98	−2.62	−4.60	0.64	+0.005
11·12·13	9.78	−1.88	−3.03	−4.90	1.15	+0.006
12·13·14	10.83	+1.20	−1.91	−0.72	3.11	+0.004
13·14·15	353.18	+1.79	−2.99	−1.19	4.78	−0.004
14·15·16	23.60	−2.40	−2.59	−4.99	0.19	+0.005
15·16·17	358.81	−1.73	−3.14	−4.86	1.41	+0.009
16·17·18	343.32	−1.43	−2.93	−4.35	1.50	+0.011
17·18·19	342.61	−0.81	−1.50	−2.31	0.69	+0.009
18·19·20	28.21	−0.72	−0.89	−1.61	0.17	+0.009

Table 2 shows the calculated strain parameters of triangles in the triangulation chain as mentioned above. An observed error in the length of each side of triangle was estimated to be smaller than 0.05 m, and therefore, the mean square error of strain rate should be smaller than about 5×10^{-5} per year.

3. Conditions of Ice Flow in the Allan Hills Bare Ice Field

3.1. Horizontal surface velocity and principal strain rate

The horizontal surface velocity at each triangulation station observed in the period between 1978 and 1979 is shown by vector arrows in Fig. 2, where the surface elevation is given with 10 m contour lines. As shown in Fig. 2, the horizontal velocity vectors of ice flow are principally perpendicular to the contour lines. The

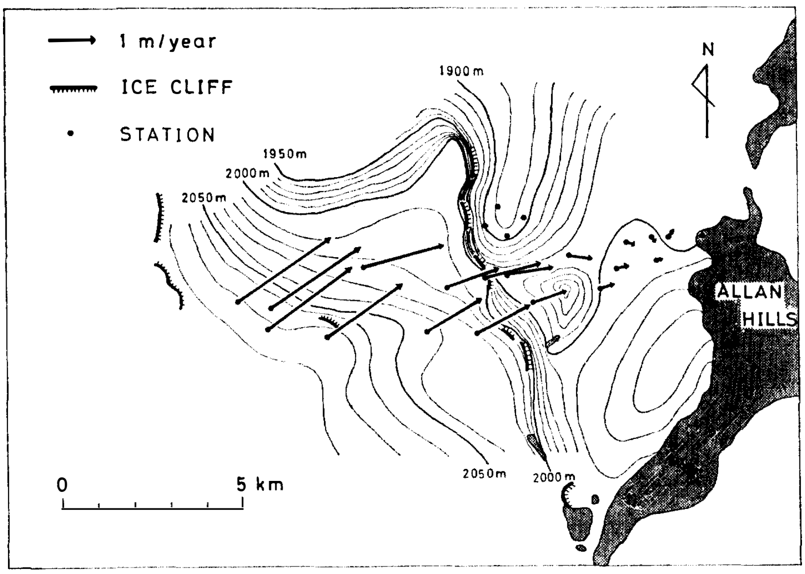

Fig. 2. Horizontal surface vectors of ice flow (m/year) and elevation of the ice sheet in the bare ice area near the Allan Hills. Surface contour lines are drawn every 10 m.

flow direction is northeastward at the farthest station (Station No. 20) and it changes clockwise by 10 to 20 degrees to the east as they approach to the nunatak. The magnitude of horizontal surface velocity is 2.51 m/year at the farthest station (Station No. 20) and gradually decreases down to zero towards the datum point on the bed-rock in the Allan Hills. It is clearly seen in Fig. 2 that the horizontal surface velocity in the bare ice field is slowed by the existence of nunataks of the Allan Hills.

Consequently, the mode of ice deformation is longitudinally compressive and it is also compressive laterally as can be seen in the pattern of the principal strains in Fig. 3. Although the direction and magnitude of the principal strain rates differ somewhat with each triangle, the direction of the maximum compression is nearly

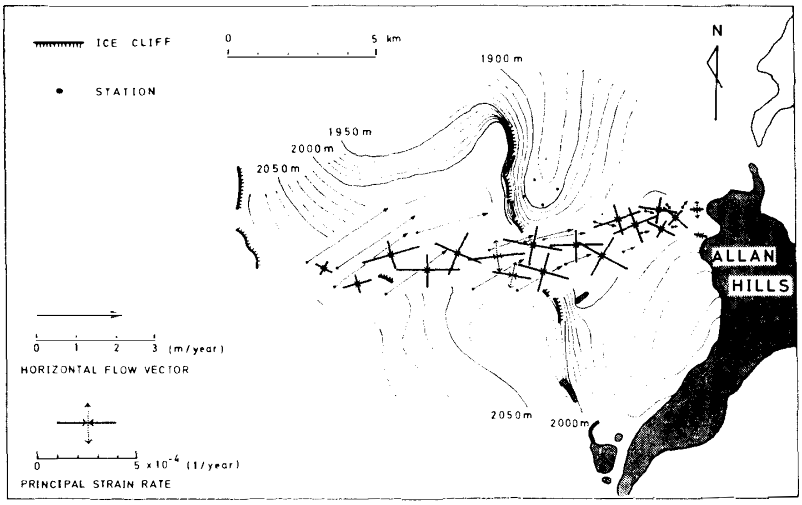

Fig. 3. Principal strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ (1/year) and horizontal surface vectors of ice flow (cm/year) in the bare ice area near the Allan Hills. Surface contour lines are drawn every 10 m.

parallel to that of the horizontal surface flow. The principal strain rates are compressive in most of the triangles, but exceptional tensile principal strain rates appear laterally in the area of triangles upstream of the ice cliff as indicated by the dotted line of arrows in Fig. 3.

Many characteristic crevasse patterns were observed on the area of the bare ice surface along the chain (Fig. 6 in NISHIO and ANNEXSTAD, 1979). However, it is considered that these crevasse patterns are caused not by the compressive strains observed in area of a triangle, but by the tensile strains in a small-scale stress condition reflected upon the ice sheet flow due to the complicated sub-ice bedrock topography of the area.

3.2. Vertical velocity of ice flow

The vertical flow velocities V_v obtained by eq. (4) are shown in Fig. 4. It can be seen in the figure that the vertical velocity of ice flow shows emergence velocity (+) ranging from 0.8 to 7.1 cm/year, being 4.5 cm/year on the average, in the area of highly accumulated meteorites around the ice cliffs extending from the southwest end of the Allan Hills to the north towards the Battlements Nunatak. The upward velocity should correspond to the horizontally convergent movement near the surface of ice sheet. To estimate the magnitude of horizontal convergence in the bare ice area, the time rate of horizontal dilatation $\dot{\Delta}$ of each triangle was computed as defined in the preceding section (2.3). As tabulated in Table 2, the dilatation rate $\dot{\Delta}$ in most of the triangle areas shows negative values, namely horizontal convergence, and the largest negative values appear in the area of highly accumulated meteorites.

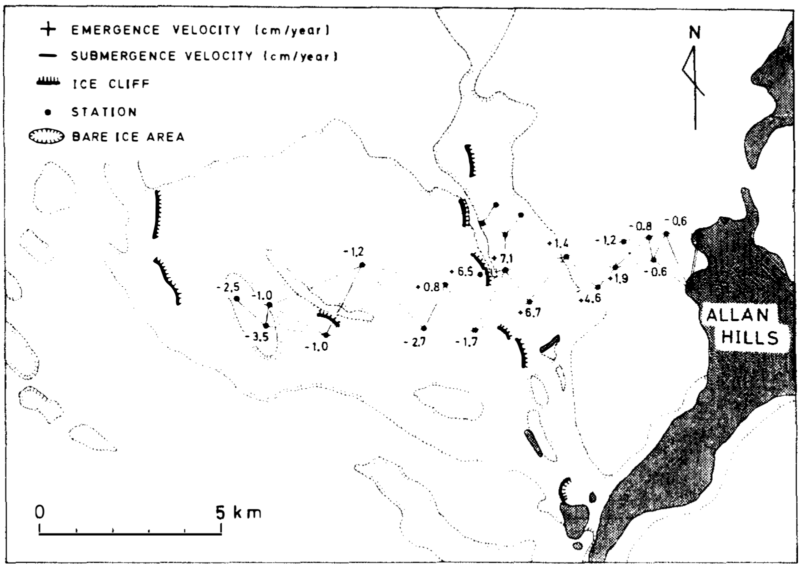

Fig. 4. Vertical velocity (cm/year) at the triangulation station in the bare ice area near the Allan Hills. Positive and negative values show emergence and submergence velocities respectively.

In the inland region of the bare ice field, the vertical flow shows a contrary tendency; very small submergence velocity (—) was found in a range from —1.0 to —3.5 cm/year, being —1.9 cm/year on the average. The downward velocity should correspond to the horizontally divergent movement near the surface, but the dilatation rate $\dot{\Delta}$ also shows negative values in the area of bare ice as shown in Table 2. As mentioned in the foregoing section (2.2), since the relative error in the vertical velocity was as large as 100% in the inland region around Stations No. 15, 17, 18 and 20, the vertical velocity in the area should be resurveyed in the time interval of more than 2 years to confirm the small submergence velocities.

3.3. Ablation rate of bare ice surface

The measurements of the accumulation of snow or the ablation of bare ice were made with the same stakes for 18 triangulation points and with additional stakes during the same period as that for measuring the horizontal and vertical movements of ice sheet surface at the triangulation station. The observational results are illustrated in Fig. 5, in which the annual ablation rate (—) at each station is given in the unit of cm/year. It can be seen in the figure that, at all measured stations (22 stations), the ablation rate measures between 1.1 and 7.0 cm/year with an average annual rate of 4.3 cm/year. If we observe the data in the figure carefully, the ablation rates of the bare ice surface alone are from 4.2 to 7.0 cm/year with an average of 5.7 cm/year, whereas the ablation rates of the firn areas covering the bare ice surface are from 1.1 to 4.5 cm/year with the average of 2.7 cm/year. This comparison

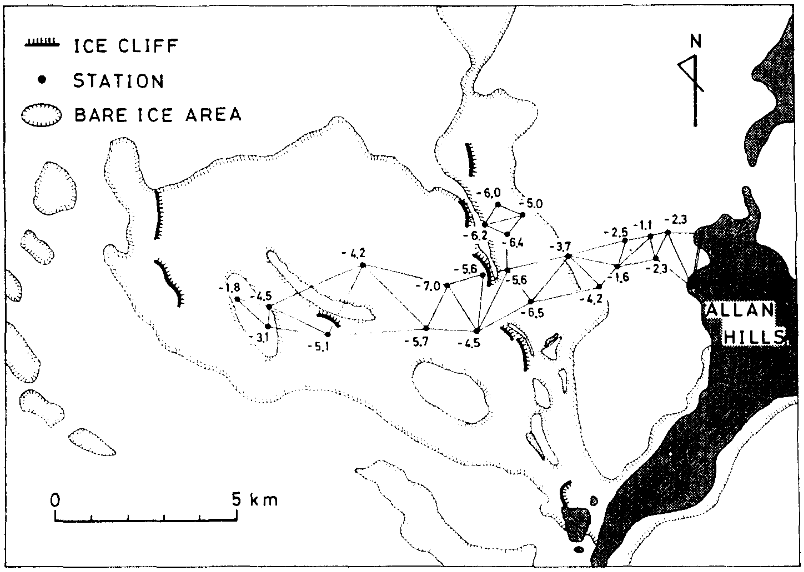

Fig. 5. Annual ablation rate (cm/year) at the triangulation station in the bare ice area near the Allan Hills.

reveals a fact that the ablation rate of the bare ice surface is remarkably larger than that of the firn area covering the bare ice surface, and this fact must be mainly due to the rapid sublimation of the exposed surface of ice. On the bare ice surface, therefore, the ablation effect should be considered to be large enough to remove completely the accumulated snow and further abrade out the surface of the emerging bare ice.

The observed average value of ablation rate of -5.7 cm/year over the bare ice surface is a little larger than or approximately equivalent to the average value of the emerging flow velocity ($+4.5$ cm/year) in the area of highly accumulated meteorites.

Therefore, it may be concluded that in this area the bare ice mass is coming out upwards from the lower part of the ice sheet with an annual upward velocity of about 5 cm/year and this emergence is also being continuously compensated with the ablation of about 5 cm/year. Thus, the bare ice surface is maintained in an almost steady state in the bare ice area near the Allan Hills where the highly concentrated area of meteorites is existing, and the meteorites contained in ice are constantly appearing onto the surface.

3.4. Longitudinal variations of ice flow, surface strains and topographic features

Fig. 6 shows the longitudinal variations against the direction of triangulation chain of the horizontal surface velocity V_h, the vertical velocity of the ice flow V_v, the ablation rate $\dot{A}$, the principal strain rate $\dot{\varepsilon}_1$, the rate of surface dilatation $\dot{\Delta}$, the rate of maximum shear strain $\dot{\gamma}_{max}$, the rate of rotation of the principal axis $\dot{\omega}$ and the vertical profile of the ice sheet. The pattern of variation in the values of horizontal and vertical velocities, ablation rate and strain parameters mentioned in the preced-

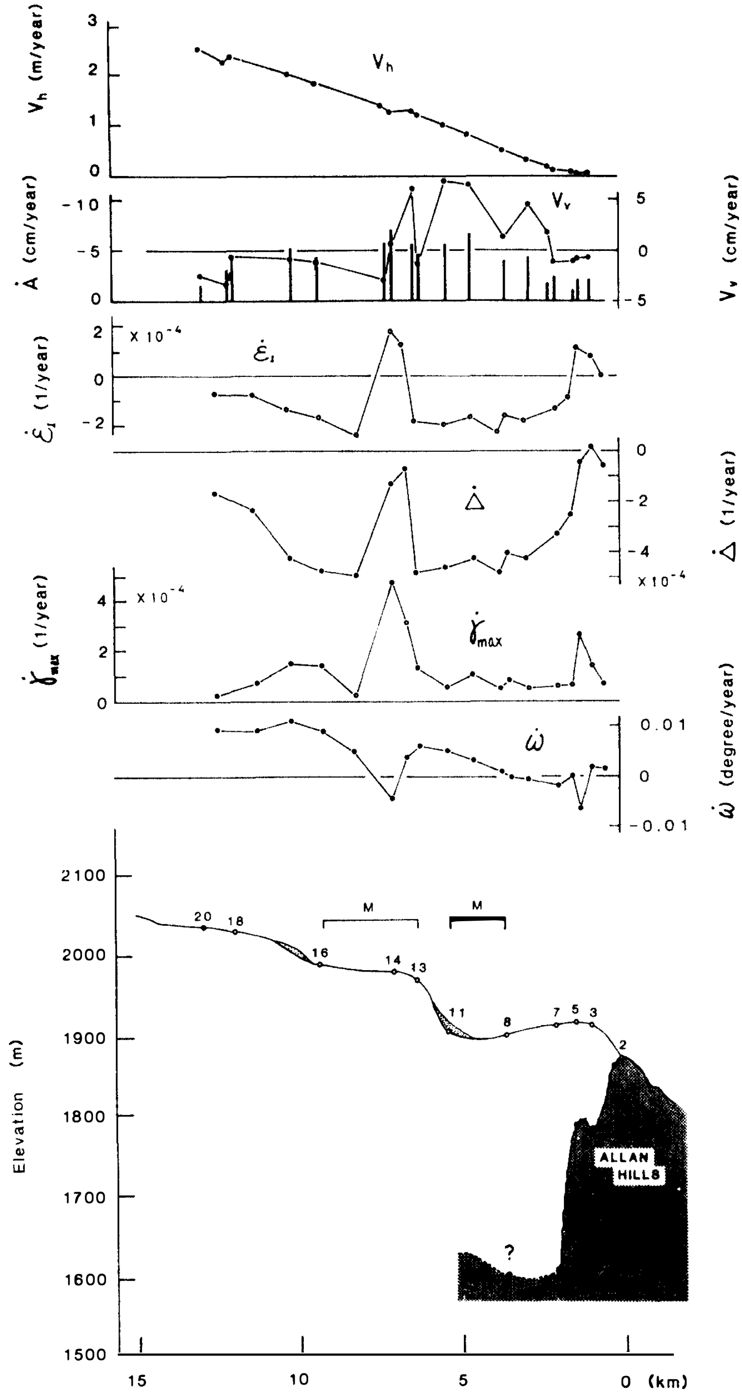

Fig. 6. Variations along the triangulation chain of the horizontal surface velocity V_h, the vertical velocity V_v, the ablation rate $\dot{A}$, the maximum principal strain rate $\dot{\varepsilon}_1$, the surface dilatation $\dot{\Delta}$, the maximum shear strain rate $\dot{\gamma}_{max}$, the rotation of the principal axis $\dot{\omega}$, and the vertical profile of the ice sheet in the bare ice area near the Allan Hills.

ing sub-sections is seen clearly in Fig. 6.

Fig. 6 shows clearly the gradual increase in the horizontal velocity from the datum point to the inland area, and the large upward velocity under the ice cliff and the high ablation rate of about 5 cm/year in the area of highly accumulated meteorites. Just above the ice cliff, the principal strain rate $\dot{\varepsilon}_1$ shows tension, the dilatation in two dimensions is approximately equal to zero, and the maximum shear strain shows a maximum value. Therefore, these data lead to the conclusion that a remarkable boundary between two different modes of ice movement exists around the ice cliffs.

4. Summary and Concluding Remarks

To elucidate the mechanism of accumulation of a large number of meteorites, studies of the ice flow in the bare ice area near the Allan Hills were carried out during the last two seasons in 1978–79 and 1979–80, and the obtained results of characters of the ice flow in the area are given in the present paper together with methods of data reductions. However, since the relative error in the vertical velocity was as large as 100% in the inland stations as mentioned in the preceding sub-section, it is important not only to resurvey the vertical velocity in the time interval of more than 2 years to confirm the small submergence velocities, but also to carry out more detailed radio echo sounding in the bare ice area to make clear the sub-ice bedrock topography which is reflecting upon the ice sheet flow.

Obtained results on horizontal and vertical velocities of ice, surface strains and ablation rate in the region along the triangulation chain are summarized as follows:

1) The horizontal surface velocity shows the value of 2.51 m/year at the farthest station from the datum point on the bedrock at the Allan Hills and gradually decreases down to zero towards the nunataks of the Allan Hills.

2) Direction of ice flow is northeastward at Station No. 20 and it changes clockwise by 10 to 20 degrees with an approach to the datum point.

3) Direction of ice flow coincides approximately with the direction of the maximum surface slope.

4) The mode of surface deformation is generally compressive along the direction of ice flow. Compressive strains are predominant along the triangulation chain and the surface dilatation shows negative values, *i. e.*, horizontal convergence.

5) The vertical velocity is emergent flow (+), *i.e.*, upward velocity of ice, in the region of high meteorite concentrations with an average emergent flow of approximately 5 cm/year, whereas the vertical velocity is submergent flow (—), *i.e.*, downward velocity in the inland region.

6) In the area of high meteorite concentrations, the ablation rate (about 5 cm/year) is approximately equal to the upward movement of ice flow.

From the above-stated results of the movement and ablation of ice sheet surface in the bare ice area near the Allan Hills, it may be concluded that the ice mass flowing down towards the Allan Hills loses gradually the horizontal velocity by the presence of the Allan Hills, but gains the upward velocity to the surface under the ice cliff, probably owing to the bedrock topography. Upward of ice of about 5 cm/year is continuously reduced by the ablation of about 5 cm/year of the surface. Thus the bare ice surface, where many meteorites are concentrated, is maintained in an almost steady state. Also the horizontal dilatation in this area indicates the horizontal convergence of ice flow.

It seems that these conditions of ice flow are favorable for accumulation of meteorites which have fallen in the snow accumulation area inland of the Allan Hills, and for the NAGATA's (1978) hypothetical mechanism of concentration of a large number of meteorites within a remarkably small area of the bare ice surface.

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