FLOW LINE OF THE ICE SHEET OVER MIZUHO PLATEAU

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Abstract: Flow lines of the ice sheet surface in Mizuho Plateau, East Antarctica were deduced from the results of observations of topographic features of the surface and measurements of surface flow of the ice sheet. This paper gives the distribution of paths of ice flow over Mizuho Plateau, and also the results of surface strains of the ice sheet measured by the square strain grids. Tensile strains whose directions were roughly parallel to the directions of the ice flow were predominant almost all over Mizuho Plateau. Considerably large compressive strains were observed in such regions with remarkable surface depressions as Mizuho Camp. The ice mass of 4.5×10^9 ton a year was estimated to pass across the vertical cross section along Route A (from A033 to S240), while 3×10^9 ton a year across Route S (from S124 to S240), both towards the Shirase Glacier.

1. Introduction

One of the important subjects of the Glaciological Research Program in Mizuho Plateau is to obtain the areal distribution of the velocity of ice flow and to study the dynamical behaviors of ice in this region. Direct measurements of the surface flow velocity were carried out by the survey of a 250-km long triangulation chain connected with the Yamato Mountains; obtained in detail were the surface movement and deformation of the ice sheet along the parallel of 72°S (NARUSE, 1975, 1978). In such an inland region that has no ice-free rocks to serve as fixed points, it is hard to make observations of the absolute values of the ice flow. A strain grid is easily surveyable and useful for obtaining valuable information on conditions of ice deformation. The surveys of seven square strain grids in Mizuho Plateau in 1969–1975 gave the distribution of principal strain, its direction and other parameters on the ice deformations at the surface.

Topographic contours of the ice surface were obtained over Mizuho Plateau, from which the divides of the drainage area were deduced (SHIMIZU *et al.*, 1978a). The flow lines of the ice sheet were determined by using the data of ice flow vectors and the surface contours of the elevation, on the assumption that a flow line should be normal to a contour line. This paper describes first the results of the survey of the square strain grids and shows secondly the surface flow lines in the drainage area of the Shirase Glacier and in its neighboring areas.

2. Distribution of Strains Measured by Square Strain Grids

The square strain grids of 1 km in each side were installed separately at nine stations over Mizuho Plateau in 1969–1970 (NARUSE *et al.*, 1972). Seven of the grids were resurveyed during the period from 1970 to 1975 (NARUSE *et al.*, 1972; SATOW, 1977). Locations of these strain grids are shown in Table 1. Two grids at C80 and W55 were found missing during the oversnow traverses in 1973–1975: the stakes originally about 2 m high above the snow surface had been buried under the snow accumulated in a period of four years.

Table 1. Locations and dates of survey of seven square strain grids.

Station	Latitude (S)	Longitude (E)	Elevation (m)	Ice thickness (m)	Date of survey	
					1st	2nd
S 40	69°04.7′	41°07′	1142	1100	5 Nov. 1969	22 Jan. 1971
S 100	69°38.1′	42°50′	1680	1368	10 Nov. 1969	10 Nov. 1970
S 160	70°40.2′	43°06′	2058	1419	14 Nov. 1969	16 Jan. 1971
S 200	71°19.4′	43°00′	2309	2385	18 Nov. 1969	20 Jan. 1974
C 37	71°07′53″	37°27.5′	1853	1656	16 Jan. 1970	25 Nov. 1973
Y 200	71°46′13″	48°55′58″	2880		27 Nov. 1970	26 Oct. 1974
Mizuho Camp	70°41′53″	44°19′54″	2230	2095	18 Nov. 1970	5 Feb. 1975

Methods of measurements and calculations of the surface strain of ice are the same as those of the triangulation chain; they are described in detail in another article by NARUSE (1978). The mode of deformation was examined firstly by using the observed data of the five-stake grid at Mizuho Camp. The result showed that the homogenious strain held approximately in the area of 1 km^2 (NARUSE, 1978).

Strain rates at each station were calculated on the four respective triangles divided by two diagonals of the square, assuming the finite homogeneous strain to all grids. Results of calculation of strain rate are tabulated in Table 2. Notations in the table are as follows:

α: Direction of the principal axis of a strain ε_1 (see below), indicated by the azimuth from 0° to 180° in true (0°: North; 90°: East; 180°: South).

$\dot{\varepsilon}_1, \dot{\varepsilon}_2$: Principal strain rate per year. The positive sign indicates extension and the negative sign contraction. The strain ε_1 signifies the algebraically maximum value among the strains in the whole directions; ε_2 the algebraically minimum value.

$\dot{\Delta}$: Rate of the change of area per year, namely dilatation.

$\dot{\gamma}_{max}$: Maximum shear strain rate per year. The directions of it are $\alpha \pm 45°$.

Table 2. Results obtained from square strain grids.

Station	Triangle	α (degree)	$\dot{\varepsilon}_1$ (1/year)	$\dot{\varepsilon}_2$ (1/year)	$\dot{\Delta}$ (1/year)	$\dot{\gamma}_{max}$ (1/year)
S 40	(1)	159.6	$+4.6\times10^{-4}$	$+0.4\times10^{-4}$	$+5.0\times10^{-4}$	4.2×10^{-4}
S100	(1)	109.8	$+4.0\times10^{-4}$	-1.0×10^{-4}	$+3.0\times10^{-4}$	5.0×10^{-4}
	(2)	108.4	+4.0	−0.8	+3.3	4.8
	(3)	109.7	+4.0	−0.8	+3.2	4.8
	(4)	107.4	+4.1	−1.0	+3.1	5.1
	mean	108.8	+4.0	−0.9	+3.1	4.9
S160	(1)	104.0	$+4.2\times10^{-4}$	-7.6×10^{-4}	-3.4×10^{-4}	11.8×10^{-4}
	(2)	108.0	+3.7	−7.0	−3.2	10.7
	(3)	107.4	+5.0	−7.2	−2.2	12.1
	(4)	104.0	+3.3	−7.0	−3.7	10.3
	mean	105.9	+4.0	−7.2	−3.1	11.2
S200	(1)	159.2	$+4.6\times10^{-4}$	-2.1×10^{-4}	$+2.5\times10^{-4}$	6.7×10^{-4}
	(2)	158.1	+4.8	−2.1	+2.8	6.9
	(3)	158.1	+4.7	−2.0	+2.7	6.7
	(4)	158.8	+4.8	−2.1	+2.7	7.0
	mean	158.5	+4.7	−2.1	+2.6	6.8
C 37	(1)		$+0.2\times10^{-4}$	-0.1×10^{-4}	$+0.1\times10^{-4}$	0.2×10^{-4}
	(2)		+0.1	−0.8	−0.7	0.9
	(3)		+0.2	−0.3	−0.1	0.5
	(4)		+0.2	−0.6	−0.5	0.8
	mean	74.1	+0.2	−0.5	−0.3	0.6
Y200	(1)		$+0.3\times10^{-4}$	-0.3×10^{-4}	$+0.1\times10^{-4}$	0.6×10^{-4}
	(2)		+0.3	−0.4	−0.1	0.8
	(3)		+0.4	−0.4	0.0	0.8
	(4)		+0.4	−0.5	−0.1	0.9
	mean	127.2	+0.4	−0.4	0.0	0.8
Mizuho	(1)	116.9	$+1.0\times10^{-4}$	-4.1×10^{-4}	-3.1×10^{-4}	5.1×10^{-4}
Camp	(2)	118.0	+0.9	−4.2	−3.3	5.0
	(3)	116.2	+0.9	−4.0	−3.0	4.9
	(4)	117.2	+0.7	−3.9	−3.2	4.6
	mean	117.1	+0.9	−4.0	−3.1	4.9

If the absolute values of ε_1 and ε_2 are both small, the dilatation Δ is equal to $\varepsilon_1+\varepsilon_2$; maximum shear strain γ_{max} is equal to $\varepsilon_1-\varepsilon_2$.

As are noted in the Table and expected from the homogeneous strain, very close values of strain rates were obtained from the four triangles. Only one triangle was available for the calculation at the grid S40, because of a serious error in the survey of the fourth stake. Strain rates at C37 and Y200 showed such small values as $2–5\times10^{-5}$ per year. They are considered to be almost comparable with the magnitude of observational errors which are estimated at 2×10^{-5} per year. Such small strain rates were not observed among the results of the triangulation chain along 72°S except the region in the vicinity of the Yamato Mountains where the surface flow velocities were very small. The small strain rates at stations C37 and Y200 could be understood as caused by very low horizontal velocities at the western and eastern fringes of the Shirase drainage basin (SHIMIZU *et al.,* 1978a). Tensile strains were predominant, namely large positive dilatation, at S40, S100 and S200. Larger compressive strains than tensile strains in the absolute values were observed at S160 and Mizuho Camp (see Fig. 1). It may have been caused by the effects of the surface depressions in the regions.

3. Flow Line

Flow lines over the ice sheet of Mizuho Plateau were determined on the following two bases:

(1) A flow line is strictly parallel with a flow vector along Route A where the direct measurements of ice flow were made by the triangulation survey (NARUSE, 1978).

(2) A flow line in other regions should be normal to the surface contour line of the ice sheet which was obtained by using the elevations of stations along the oversnow traverse routes and also the data of the maximum surface slope at some stations (SHIMIZU *et al.,* 1978a). NARUSE (1978) examined the difference of horizontal angles between the direction of ice flow and that of the maximum surface slope along the triangulation chain, and showed that the two directions coincided approximately having the standard deviation of 9 degrees on the ice sheet with even slope.

Distribution of flow lines over the lower part of the Shirase drainage basin and its neighboring basins is shown in Fig. 1, together with surface flow vectors and principal strains along the triangulation chain, and also the principal strains obtained from the square strain grids at S40, S100, S160, S200, C37 and Mizuho Camp. It is clear from the figure that the direction of the maximum extension of surface strain was approximately parallel with the flow line. Determination of ice divides between the different drainage basins may be supported by the pattern of principal strains at S40, S100 and so on; namely, station S40 should be located in the Prince Olav drainage basin and S100 in the Sôya drainage basin as shown by SHIMIZU *et al.* (1978a). It is also noted from the figure that the flow lines in the Shirase drainage basin are strongly converging into the Shirase Glacier. Therefore, the magnitude of surface flow velocity must increase considerably from

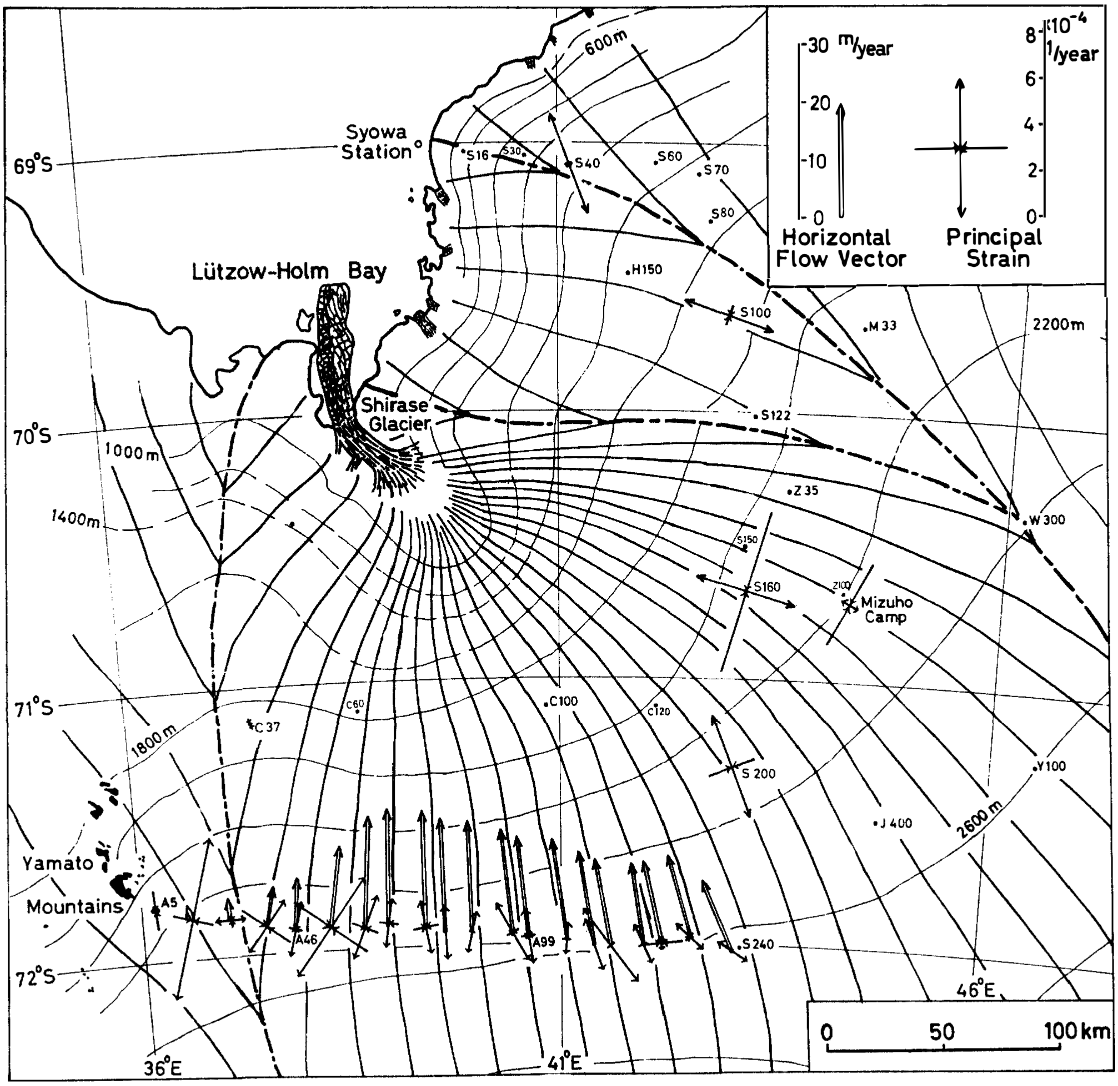

Fig. 1. Flow lines of the ice sheet over Mizuho Plateau, and distribution of the horizontal vectors of ice flow and the principal strains (maximum extension and contraction) obtained from the triangulation chain along Route A and the square strain grids.

Ice divides of the drainage basins are shown by dot-dash lines. Surface contours of the ice sheet are drawn for every 200 m.

the inland area towards the coast; actually, the velocity was obtained as 20 m/year at the central part of Route A (NARUSE, 1978) and 2500 m/year at the terminus of the Shirase Glacier (NAKAWO *et al.*, 1978). It is presumed that about 5000 years are necessary for the ice mass to travel from the triangulation chain (72°S) to Route C (71°S) and 1500 years from Route C to the outlet of the Shirase Glacier (70°S), after a rough calculation based on the data of the surface flow velocity and ice thickness at 72°S, 71°S and 70°S, and also taking into account the variations of the width between the flow lines. One must keep in mind this long time scale for considering the mass budget of the ice sheet.

NARUSE (1978) derived a relation from the triangulation survey that the surface flow velocity was almost proportional to the second power of the surface slope and to the third power of the ice thickness, based on the theory of laminar flow of ice (NYE, 1952). By using this relation, surface velocities were roughly estimated at some stations over Mizuho Plateau, where the data were available as to the ice thickness measured by the radio echo sounding (SHIMIZU *et al.*, 1972; NARUSE and YOKOYAMA, 1975) and the surface slope obtained by the skyline measurements (WATANABE and AGETA, 1972). Calculated velocities are shown in Table 3, together with the measured velocities at S16 (SHIMIZU *et al.*, 1975) and at S240. Although the calculated velocity might include a large error, the high values obtained at S200 and around W40 are considered to have resulted from one of the main tributary flows of the Shirase Glacier and of the Rayner Glacier (see Fig. A, at the end of this volume), respectively. While, the

Table 3. Estimation of surface flow velocity from the data of ice thickness and surface slope.

Station	Latitude (S)	Longitude (E)	Elevation (m)	Ice thickness (m)	Surface slope	Calculated velocity (m/year)
S 16	69°02′	40°03′	554	—	—	4.5*
S 30	69 03	40 42	988	929	1/76	9
S 40	69 05	41 07	1142	1100	1/106	8
S 60	69 05	42 02	1369	1332	1/149	7
S 80	69 17	42 35	1516	1522	1/181	7
S100	69 38	42 50	1680	1368	1/140	9
S150	70 30	43 04	2022	1317	1/115	12
S200	71 19	43 00	2309	2385	1/229	18
S240 (A164)	72 00	43 10	2639	—	—	13.6*
Z 35	70 17	43 38	2070	1728	1/146	16
Z95—Z100☆	70 39	44 15	2196	2056	1/199	15
Y90—Y100☆	71 14	46 25	2595	2249†	1/306	8
Y305	70 52	49 56	2677	2052	1/229	11
Y405	70 00	50 46	2449	2180	1/186	20
W 26	69 06	50 22	1942	1881	1/196	12
W31—W49	69 23	49 28	1942	2069	1/152	26
W225	69 52	47 40	2316	1283	1/123	9

Mark ☆ in the column of station: Mean value of several stations among these stations.
† in the column of ice thickness: Thickness calculated from gravity anomalies.
* in the column of velocity: Measured velocity by the triangulation method.
Locations of stations are shown in Fig. A in this volume.

small velocities in the vicinity of the coast, namely the region from S16 to S80, may be ascribed to the effect of divergence of the flow lines as shown in Fig. 1.

The amount of ice which flows through a vertical cross section along a portion of the triangulation chain, 220 km long from the west boundary of the Shirase drainage basin to S240 (A164), was estimated at 4.5×10^9 t/year, multiplying the cross-sectional area by the mean flow velocity estimated from the surface velocity. The amount of ice discharge across obliquely a portion of Route S, 220 km long from S240 to the north boundary of the Shirase drainage basin, namely S124, was estimated at 3×10^9 t/year by using the calculated velocities shown in Table 3. Density of ice was taken as 0.85 g/cm^3. Then, the total of 7.5×10^9 t of ice flows annually towards the Shirase Glacier through the vertical section along a rectangular line which cuts the Shirase drainage basin at 2000–2600 m in elevation. This amount of ice discharge is compared with that at the terminus of the Shirase Glacier and also with annual accumulation of snow over the drainage area, through the discussion of the local mass budget of the ice sheet (SHIMIZU *et al.*, 1978b).

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