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Structural and morphological characteristics of Soler Glacier, Patagonia

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Abstract

Soler Glacier, located in the Northern Patagonia Icefield, is a temperate, outlet glacier, whose elevation ranges from about 350 m near the snout to over 3000 m near Mt. Hyades with a total area of 50.9 km^2. The accumulation and ablation areas were measured to be 36.4 km^2 and 14.5 km^2, respectively. Of the accumulation area, 28 km^2 or 77 percent lies in the icefield, while the remainder lies on the southeastern slope of Mt. Hyades.

Structure and morphology of the glacier surface were mapped and analyzed utilizing vertical aerial photographs of about 1 : 5, 300 scale. Two distinctive ice bodies are evident ; the debris covered northern half and the clean southern half, which are related to the supply sources, the Mt. Hyades slope and the icefield, respectively. With close analyses of photographs, seven separate ablation ice bodies were recognized below the icefalls and rock cliffs. Of these two come from the icefield through an icefall about 700 m high and avalanching, while five are nourished by the Mt. Hyades slope through icefalls and avalanching.

Five sets of ogive patterns can be recognized on the glacier surface. In the center of the glacier, 32 pairs of white and dark bands were identified in a distance of 5.5 km, yielding an average annual flow speed of 170 m. From the ogive spacings, flow speeds of about 100 m/a near the snout and 300 m/a below the rock cliffs were deduced. The crevasse patterns indicate that the majority have been caused by the friction of valley walls, often combined with either compressional or extending flow.

In two years between 1983 and 1985, the glacier surface has lowered by close to 10 m in the lower reach area of the glacier.

1. Introduction

Preliminary analyses of the structure and morphology of Soler Glacier (Aniya and Naruse, 1985) enabled us to direct special attention to unidentified features during the field season of 1985-86. Again, utilizing the enlarged 6×6 fomat vertical aerial photographs at a scale of about 1 : 5,300 (Aniya, 1987a), the glacier surface was mapped incorporating field data, and compared with that produced two years ago in order to detect the changes which occurred in two years. New data on the boundaries of the accumulation area in the icefield have become available since, and these made it possible to discuss the accumulation and ablation areas in detail.

2. Ablation and accumulation areas

Soler Glacier is a temperate, valley glacier located on the eastern side of the Northern Patagonia Icefield (see Map 2, folded in). Since about 50 percent of the ice, in terms of the surface area, comes from the icefield through an icefall, the glacier can be regarded as an outlet glacier. The remainder is supplied from the southeastern slope of Mt. Hyades (3078 m) through icefalls and avalanching.

Detailed analyses of the vertical aerial photographs enabled us to identify seven individual ice bodies below the icefalls and rock cliffs in the ablation area : two originate from the icefield ; and five come from the Mt. Hyades slope (Fig. 1). The ice from the icefield spills into the valley through an icefall about 700 m high : however, at the lower part (elev. *ca.* 1000

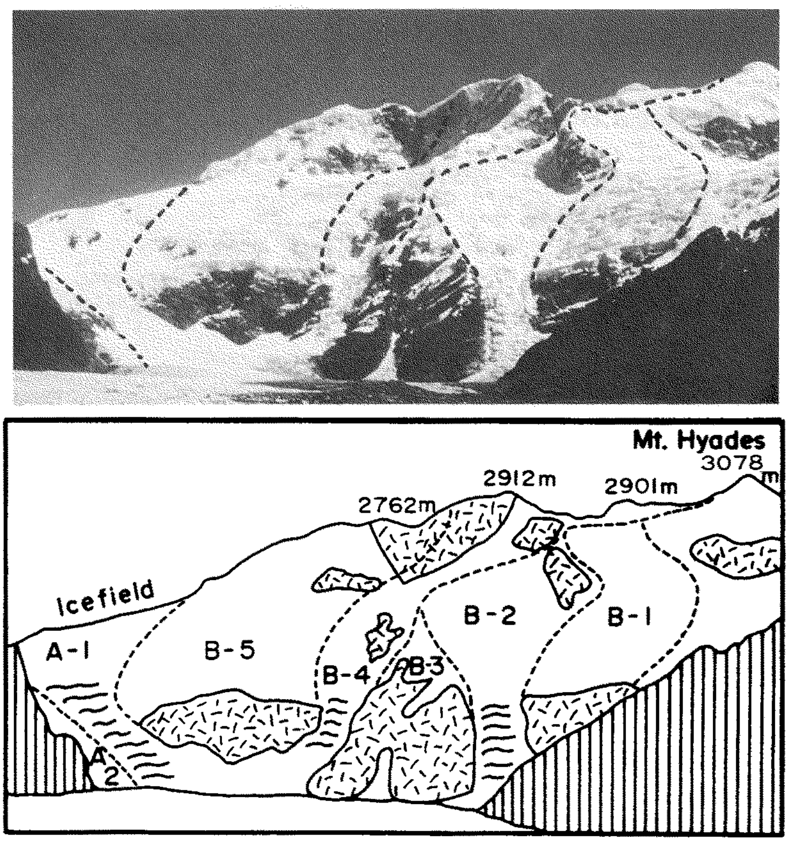


Fig. 1. Photograph showing the seven sources for the ablation bodies: the southeastern slope of Mt. Hyades (B1-5) and a big icefall leading to the icefield (A1-2). Heights of peaks, 3078 m, 2901 m and 2912 m were determined by the triangulation survey by Naruse in November 1985.

m) of the southern side, rock cliffs are exposed and avalanching is very active. From this avalanche fan starts the distinctive ice body A-2, although it becomes obscure after flowing about 1 km. Five ice bodies, coming from the southeastern slope of Mt. Hyades, are nourished through icefalls (B-2, B-3 and B-4) and avalanching (B-1, B-4 and B-5). Ice bodies B-1, B-2, and B-3, merge into one around the middle reach of the glacier (Fig. 2).

Although the drainage boundaries of Soler Glacier in the icefield were estimated in the previous report from aerial photographs and the map (Aniya and Naruse, 1985), some modification became necessary after a ground survey was carried out with altimeter readings (Casassa, 1987). Figure 2 shows the complete drainage area of Soler Glacier based on the survey data, along with contours at 250 m intervals. The present snout lies at an elevation of around 350 m, while the highest point is over 3000 m, with an area of 50.9 km^2. An extensive accumulation area spreads out around the elevations of 1600-2000 m in the icefield. Drainage areas corresponding to each ice body of the ablation area were determined on the 1 : 50,000 topographic map with the aid of photographs (see Fig. 2). Then an elevation of 1350 m was adopted as an equilibrium line (Casassa, 1987) and the accumulation and ablation areas were measured (Table 1). The total accumulation area is 36.4 km^2, of which about 28 km^2 or 77 percent lies in the icefield, while the ablation area is 14.5 km^2. The relatively flat part of the ablation area, below the elevation of 750-850 m, is about 11.7 km^2.

In order to examine the characteristics of the glacier profile, a hyposographic curve was drawn (Fig. 3). In this graph, the square root of the cumulative area was plotted as the absissa and the corresponding elevation as the ordinate. Therefore, it shows a hypothetical, ideal or average profile of the glacier drain-

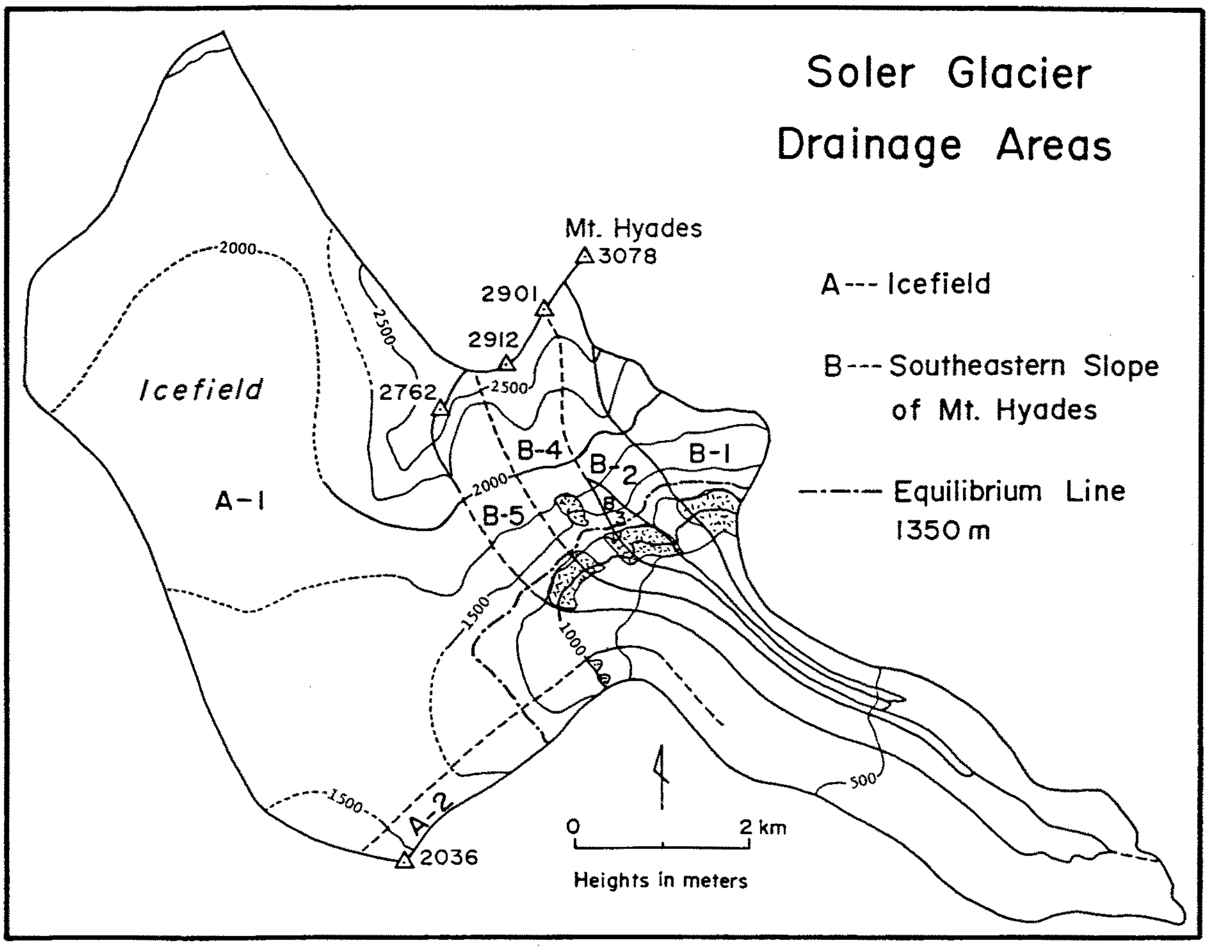


Fig. 2. Soler Glacier drainage area. Map based on the 1 : 50,000 topographic map "Cerro Hyades" published by Instituto Geográfico Militar of Chile. Boundary and elevations in the icefield were determined by Gino Casassa in November-December 1985, from which dashed contour lines were drawn.

Table 1. Soler Glacier Area Statistics

Ice Body	Accumulation Area (km^2)	Ablation Area (km^2)	Ratio
A-1	29.5 }	7.4	4.1:1
A-2	0.9 }		
B-1	1.6 }	2.3 }	0.7:1 }
B-2	1.1 } 2.9	0.8 } 3.6	1.3:1 } 0.8:1
B-3	0.2 }	0.5 }	0.4:1 }
B-4	1.7	1.0	1.7:1
B-5	1.4	2.5	0.6:1
Total	36.4	14.5	2.5:1
Grand Total	50.9		

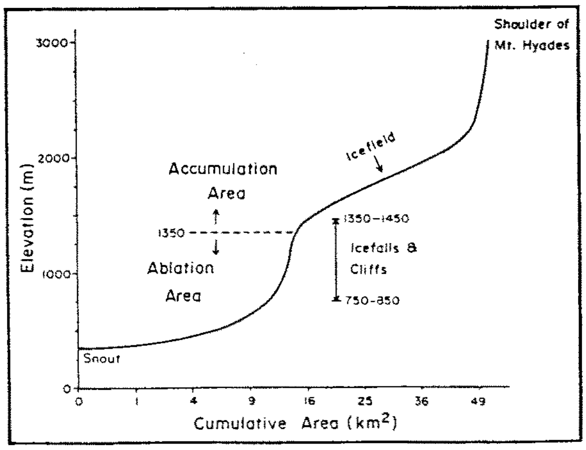


Fig. 3. Hypsographic curve of Soler Glacier drainage area, showing an averaged profile.

age area. On this figure the flat part of the ablation area, steep icefalls and rock cliffs, relatively flat icefield and steep slope of Mt. Hyades are clearly shown. Incidentally, the top elevation of rock cliffs and the B-2 and B-4 icefalls lie around 1350 m, the same as the equilibrium elevation.

3. Surface features

(1) *Debris cover and medial moraine*

The structure and morphology of the glacier surface were mapped using enlarged vertical aerial photographs (Fig. 4). A striking feature of the surface is a contrast between the clean southern half and the debris-covered northern half of the glacier, which is related to the supply sources. While the clean ice comes from the icefield without collecting detritus, those ice bodies fed by avalanching from the Mt. Hyades slope contain a large amount of rock fragments. Although coming from the Mt. Hyades slope, the B-2 body is relatively clean, because it is supplied through an icefall. On the other hand, the B-4 body is not clean even though the supply is through an icefall. Field observations indicate that avalanching in the icefall is also very active, involving a lot of rock debris. The B-3 body has a wide exposure of rocks, resulting in a large supply of debris, which becomes a medial moraine standing out due to insulation effect and squeezing by ice bodies on both sides.

(2) *Ogives*

Ogives can be easily recognized on the photographs, although it was very difficult or impossible to locate some of them in the field. Details of the feature will be discussed later.

(3) *Ice mounds*

Ice mounds located on the B-5 body near the middle and lower parts of the glacier stand out more than 10 m from the surrounding surface. They are densely covered by angular rock fragments so that the ice surface is barely visible. The long axis of these rocks is generally less than 10 cm ; however, there are occasionally big boulders exceeding one meter. Consequently, it appears that these ice mounds have been produced by the insulation effect of rock cover. These rock fragments were probably supplied from the B-5 rock cliff by big rock avalanches, which occurred several tens of years ago, inferred from the ogive patterns.

(4) *Supraglacial streams*

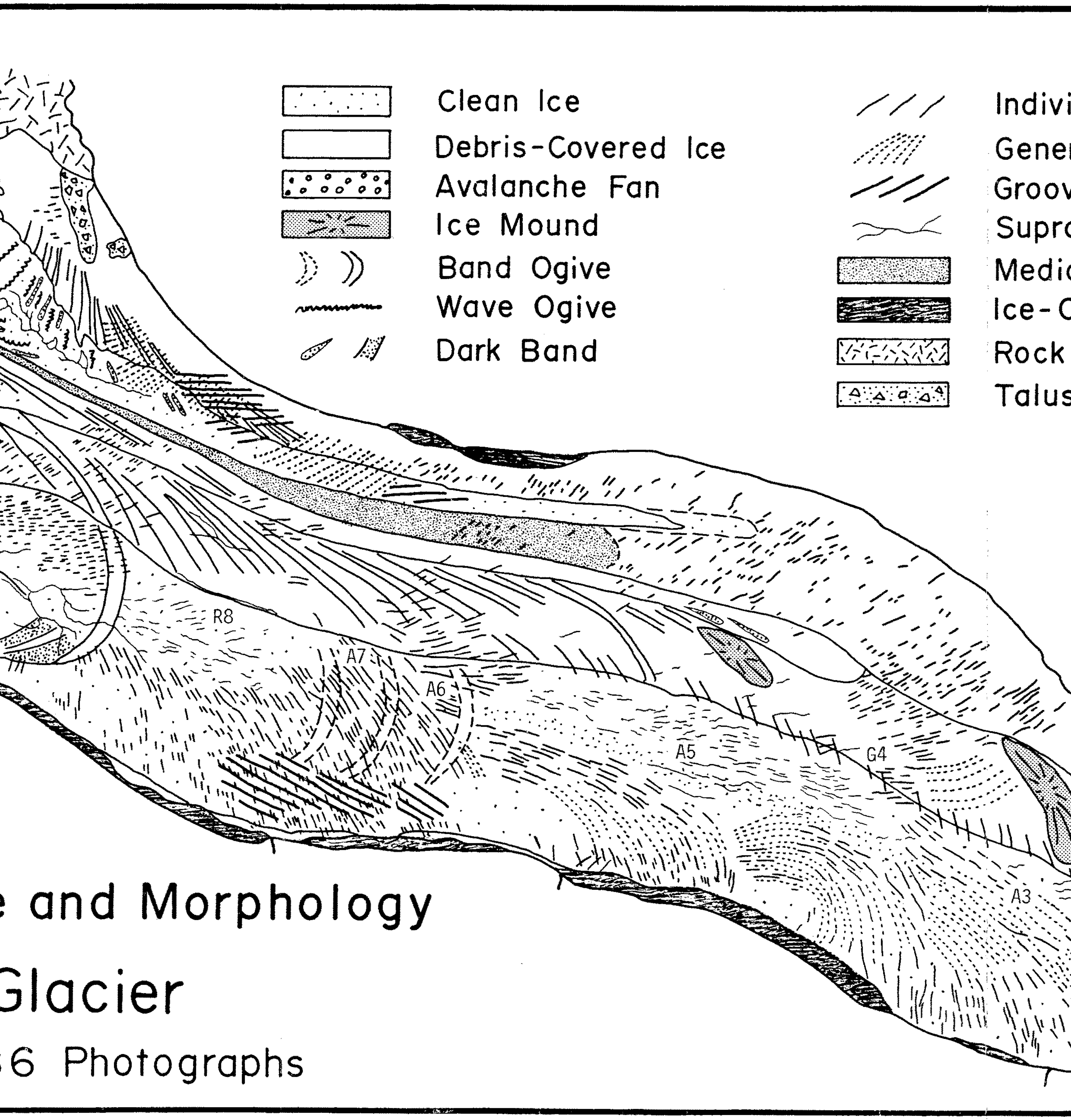
Supraglacial streams are numerous, particularly on the northern part of the A-1 body, where crevasses are less well developed. Along the border between the A-1 and B-5 bodies, near the middle of the glacier, deeply-incised supraglacial stream systems with large moulins are well developed. Moulins are particularly abundant near the middle part of the B-5 body and the lower part (around A2) of the A-1 body.

(5) *Ice-cored moraines*

The southern margin of the glacier is almost continuously rimmed by ice-cored lateral moraines, whose height above the ice edge is up to 40 m. On the other hand, they developed poorly on the northern margin of the glacier. About 150-200 m from the snout in the debris-covered area, a belt of ice-cored moraines about 800 m long, almost parallel to the glacier snout, has appeared since 1983-84. Their heights range from few meters to around 20 meters. At present, 18 mounds and ridges are recognized. They are covered mainly by coarse sand of well-rounded nature, with a thickness of around 10-20 cm. Their formation is discussed elsewhere (Aniya, 1987b).

(6) *Crevasses*

Crevasses are well distributed over almost all of the glacier surface ; however, except for few areas, they are no hindrance to walking. Along the northern margin of the glacier at the upper third of the B-1 and B-2 bodies are well developed crevasse patterns which run up-glacier toward the middle, indicating a pattern caused by shear stress exerted by valley walls only (Nye, 1952). This pattern can also be recognized on the A-1 body around the southwest of points A6 and A7. A crevasse pattern produced by shear stress and compressional flow, whose pattern is slightly convex downward, can be recognized on the A-1 body, from the middle part down-glacier to the area south of point A2. Around points A7, A6, and G4, a diverging pattern of crevasses from the boundary between the A-7 and B-5 bodies is conspicuous. Below icefall B-4 and avalanche fan B-5, and on the A-2 body, are a few large crevasses running close to perpendicular to the flow direction, indicating that these were caused by shear stress and extending flow. They are located where the surface slope becomes steeper. Longituidnal crevasses are characteristic near the snout area, particularly in the southern half, often forming seracs. These crevasses are thought to be relics of old ones formed in the upper region and subsequently, walls were melted out to form seracs. Water-filled crevasses



ial photographs taken on January 7, 1986.

are relatively numerous, and some deep ones, up to about 30 m, are distributed in the marginal area to the southwest of point A3.

There are features which look similar to crevasses at first sight, but are different, in the areas southwest of point A7 and on the northern margin of the B-1 body. We call these "groove" here. They run almost parallel to each other and typically cut through crevasses at an angle of about 60 degrees. They are broad and U-shaped in cross-section ; large ones are 10 -15 m deep and about 20 m wide at the top. Water does not flow along the groove floor, because crevasses cut across, making the floor jagged along the length-wise direction. The origin of these grooves is uncertain at present.

4. Ogives and flow velocity

Close examination of vertical photographs revealed five sets of ogives on the A-1, B-1, B-2, B-4, and B-5 bodies. Distinctive white bands of the ogive on the B-5 body are particularly conspicuous along the center part of the glacier. Ogives are usually found below icefalls and cliffs on which avalanching is very active. A dark ogive band is thought to represent a mass of ice which has passed through an icefall or avalanched over a cliff during a summer season (King and Lewis, 1961). Therefore, a pair of white (winter ice) and dark (summer ice) ogive bands is formed each year at the icefall, and the widths of the bands indicate the amount of annual flow. As a result, the distance between two succesive ogives can be taken as equivalent to the distance ice moved in a year at that point in a stable glacier (Paterson, 1981). The first band on the B-5 body appears around a point 1.6 km from the base of the B-5 rock cliff, and in a distance of 5.5 km toward the snout, 32 traces of the white band can be identified. Although Soler Glacier has thinned considerably in the last two years, an approximate annual average flow velocity of about 170 m could be computed.

The spacings of the paired white and dark bands were measured, and moving averages of the three points were taken and plotted against the distance from the snout (Fig. 5). There are two prominent peaks around 2.8 km and 4.8 km points where the flow velocity is faster than in neighboring areas, probably indicating an area of extending flow. Flow velocity ranges from less than 100 m/a near the snout to more

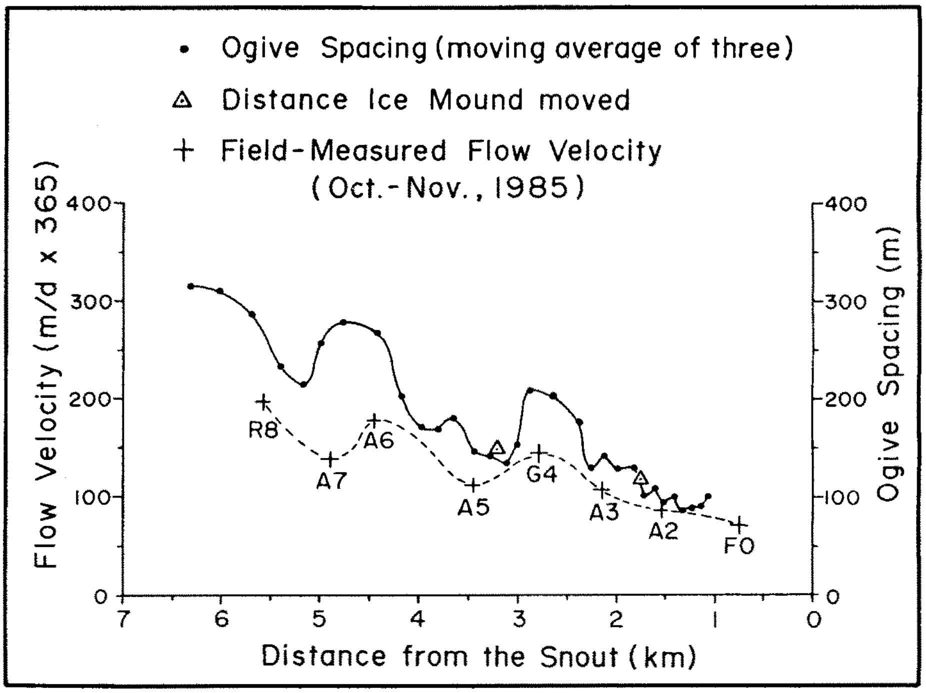


Fig. 5. Ogive spacings on 1986 photograph plotted against the distance from the snout. The distances ice mounds moved and the field data are superimposed.

than 300 m/a below the icefalls and rock cliffs. These figures indicate velocities at the border between the B-5 and A-1 bodies, where the velocity is slightly less than the maximum at the center of the A-1 body.

By superimposing Fig. 4 onto Fig. 2 of the previous report (Aniya and Naruse, 1985), the amount the two ice mounds moved in two years was measured to be 240 m and 300 m for the upper and lower mounds respectively. These data were also plotted on Fig. 5, and they agree very well with the ogive spacings ; thus proving the validity of taking the ogive spacings to be the mean annual flow velocity. The field-measured flow velocity data were also plotted (A2, A3, G4, A5, A7, and R8), after multiplying the daily average flow velocity by 365. They are generally smaller than those deduced from the ogive spacings. The wavy pattern of velocities is well synchronized with that of the ogive spacing, implying that the low-values probably result from the observation time, that is from late October to early November. It is just the beginning of summer and the amount of basal slip, which would greatly contribute to the flow (Elliston, 1962 ; Naruse, 1987), was still small.

5. Surface lowering between 1983 and 1985

The glacier surface, particularly in the snout area, was found to have lowered substantially since 1983. The height of the newly-formed belt of the ice-cored moraines indicates the general amount of the surface lowering in two years. Repeated surveys from the same ground station with a theodolite of the glacier surface along the center line between point near T2 and G4 (see Fig. 4 for location) yielded a surface lowering of about 7 m to close to 15 m (Fig. 6). On the average, the surface elevation has lowered by 9.9 m in 23 months, giving an average rate of 5.2m/a. This is considerably faster than the rate of 1-2 m deduced for the period between 1944 and 1984 (Aniya and Enomoto, 1986).

6. Summary and conclusion

The structure and morphology of Soler Glacier were analyzed from field work and aerial photo-interpretation. Seven individual ice bodies were recognized

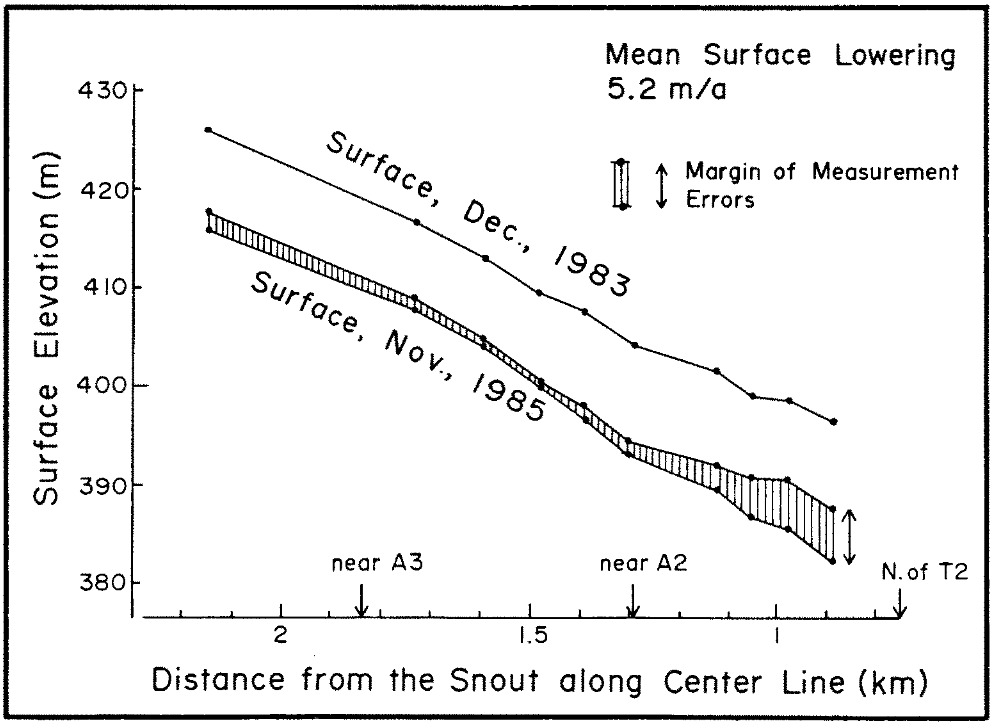


Fig. 6. Lowering of the glacier surface in two years. Measured from station β.

from the ogive patterns. The surface features which were described and analyzed included debris cover, medial moraine, ogives, ice mounds, supraglacial streams, ice-cored moraines and crevasses.

An average flow velocity of the glacier was deduced from ogive spacings to be 170 m/a. The repeated survey of the surface elevation near the snout indicates that the surface has lowered by about 10 m in two years from 1983 to 1985.

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Resumen

Características estructurales y morfológicas del Glaciar Soler, Patagonia

El Glaciar Soler, ubicado en el Hielo Patagónico Norte, es un glaciar de desagüe temperado, que alcanza alturas de más de 3.000 m cerca de la cumbre del Cerro Hyades, con un área total de 50,9 km². La Figura 1 muestra la falda suroriental del Cerro Hyades y un salto de hielo que conduce al campo de hielo. En la Fig. 2 se muestra el área de drenaje del glaciar y curvas de nivel a intervalos de 250 m. Basándose en este mapa una curva hipsográfica fue dibujada, que representa un perfil promedio del área de drenaje (Fig. 3). Los valores medidos para las superficies de acumulación y albación fueron de 36,4 km² y 14,5 km², respectivamente (Tabla 1). De este total, 28 km² o un 77% pertenece al campo de hielo mientras que el resto forma parte de la falda suroriental del Cerro Hyades.

Se mapeó la estructura y morfología de la superficie glaciar (Fig. 4), la cual fue analizada utilizando fotografías aéreas verticales a escala 1 : 5.300. Se distinguen claramente dos cuerpos de hielo ; la mitad norte cubierta por detritos y la mitad sur constituida por hielo limpio. Ambas están relacionadas con sus respectivas fuentes de alimentación: la falda del Cerro Hyades y el campo de hielo. Mediante un análisis detallado de las fotografías siete cuerpos de hielo separados fueron distinguidos en el área de ablación por debajo de los saltos de hielo y farellones. Dos de ellos se originan en el campo de hielo, siendo alimentados a través de un salto de hielo de 700 m de alto con frecuentes avalanchas, mientras que los otros cinco son alimentados por la falda del Cerro Hyades a través de saltos de hielo y avalanchas.

En dos años transcurridos entre 1983 y 1985, la superficie del glaciar ha descendido cerca de 10 m en la zona inferior del glaciar (Fig. 5).

Sobre la superficie del glaciar cinco grupos con diferente diseño de ojivas pueden ser distinguidos. Treinta y dos pares de bandas blancas y negras fueron identificados en una distancia de 5,5 km en el centro del glaciar, resultando en una velocidad promedio anual de 170 m. A partir de las separaciones entre ojivas (Fig. 6), se dedujo una velocidad de 100 m/a cerca del frente y 300 m/a debajo de los farellones de roca. Los diseños de grietas indican que la mayoría de ellas se formaron por fricción con las paredes del valle, a menudo combinado con el flujo glaciar, ya sea compresivo o extensivo.