Report 11

Structure and morphology of Soler Glacier

Masamu Aniya
Institute of Geoscience, University of Tsukuba, Ibaraki, 305 Japan
and
Renji Naruse
Institute of Low Temperature Science, Hokkaido University, Sapporo, 060 Japan

Abstract. Soler Glacier is a temperate, valley glacier about 7 km long and 1.5 km wide on the average with a current ablation area of 11.7 km^2. In terms of surface area, about 50 percent of the ice presently comes from the Northern Icefield, while the remainder is supplied from the southeastern side of Mt. Hyades. Accumulation area of the glacier is estimated to be about 44 km^2 (Icefield, 36 km^2; Mt. Hyades, 8 km^2). The ogive patterns and surface morphology indicate that the glacier actually consists of five separate bodies.

Structure and morphology were mapped and analyzed utilizing the vertical aerial photographs at a scale of about 1:8,000. Two distinctive ice bodies are clearly recognized; the northern half with debris cover, and the southern half with clean ice. Both wave and band ogives can be recognized on the surface. Presently thirty-two band ogives are counted in a distance of 5.1 km, giving an average annual flow speed of 160 m. From the ogive spacing, the flow speed near the snout is estimated at around 100 m/year, whereas near the icefall it is about 350 m/year. The crevasse pattern indicates that most of them are caused by friction with the valley walls.

The longitudinal profile shows that the average gradient is about 2.7 degrees. Cross-valley morphology is approximated by lines ranging from a nearly straight line to quartic parabolas. The ice thickness is estimated to be about 300 m and 240 m at the cross-section 6 km and 4 km from the snout, respectively.

1. Introduction

The structure and morphology of Soler Glacier were analyzed utilizing 6 × 6 format aerial photographs (Report 13), supported by the field survey and with the aid of the 1:50,000 topographic map. Description and discussion were divided into those related to the drainage, surface conditions, ogives, crevasses, and longitudinal and cross profiles with the estimation of the glacier thickness at two cross-sections.

2. Drainage areas

Soler Glacier is a temperate, valley glacier located on the eastern side of the Patagonia Northern Icefield (see Maps 1, 3 and 4, front page). It is about 7 km long from the base of icefalls and about 1.5 km wide on the average, with a current ablation area of 11.7 km^2. The glacier can be regarded as an outlet glacier because presently about 50 percent of the ice, in terms of the surface area, is supplied from the Northern Icefield through an icefall. The remainder comes from the southeastern side of Mt. Hyades through icefalls and avalanching. Detailed analyses of 6 × 6 format aerial photographs indicate that the ice is actually supplied

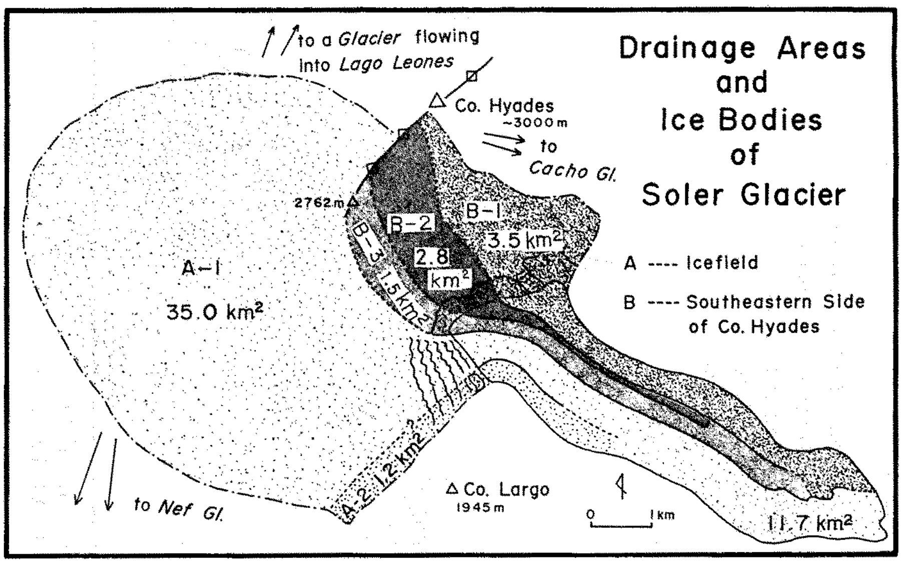

Fig. 1. Drainage areas and associated ice bodies. Ice bodies distinguished from vertical aerial photographs and the areas measured on the 1:50,000 topographic map after delineation with the aid of the photographs.

from five sources: two from the icefield; and three from the Mt. Hyades slope (Fig. 1). Ice from the Northern Icefield spills out to Soler Glacier through an icefall, which is about 1.1 km wide at the base and whose elevation ranges from 750 m to about 1450 m, with a 700 m drop in 2 km. The icefall consists of two falls, separated by a step located at elevations of 1150–1200 m. The lower half is much steeper than the upper half, with a 400 m drop in 800 m giving an average gradient of 30 degrees. At the lower part (elevation~1000 m) of the southern side of this icefall, rock cliffs whose width is about one third of the icefall (~350 m) are exposed. Here ice from the icefield avalanches down to Soler Glacier rather than flowing into the glacier, producing an avalanche fan, from which one distinctive body of ice starts (A-2).

The southeastern side of Mt. Hyades supplies ice through three distinctive feeding channels. Two of them consist of an icefall and avalanching, and the remaining one of avalanching only. Although it was difficult to delimit exactly these accumulation areas, it was attempted using the 1:50,000 topographic map (Cerro Hyades) with the aid of vertical and oblique aerial and ground photographs. Rough estimates indicate that the Northern Icefield has a catchment area of about 36 km^2, while the Mt. Hyades slope has an area of 8 km^2, totaling to 44 km^2. A detailed break down of these areas is shown in Figure 1.

3. Surface conditions

Detailed structure and morphology of the surface were mapped utilizing the vertical aerial photographs (Fig. 2). About the northern half of the glacier is covered with debris, while the southern half is of clean ice. These distinctive contrast of the surface condition is closely related to the supply source. That is, the debris-covered part is fed with ice from the Mt. Hyades slope, whereas the clean part consists of ice fed from the icefield. Although the boundary between the clean and debris-covered ice bodies is located along the A-1 and B-3 contact,

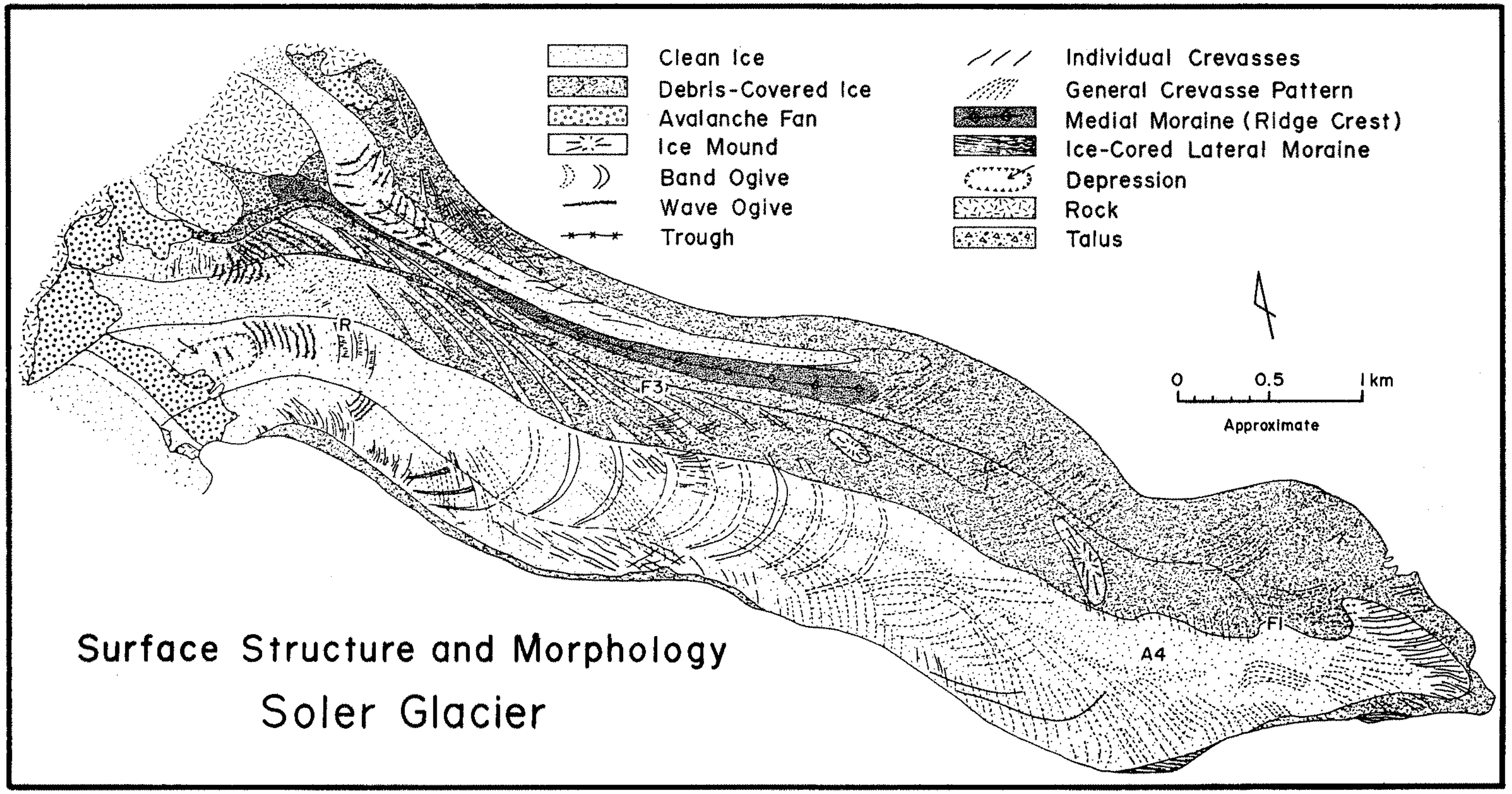

Fig. 2. Structure and morphology of the glacier surface, mapped from vertical aerial photographs. Scale determined from the distance between the two ground stations. F1, A4, F3 and R (Rock) indicate field-measured stations.

there are only very slight breaks in the ogive patterns along this contact, indicating that these two ice bodies move together as almost one body after coalescing. On the other hand, there are slight offsets in the ogive patterns along the contact of the B-2 and B-3 bodies. In terms of the general ogive patterns, two sets of ice bodies can be identified, which is not related to the surface appearance. One body is made up of ice from the B-1 area and the other from the A, B-2 and B-3 areas.

There is a medial moraine where ice bodies from the B-1 and B-2 areas merge. Rock walls located at the base of these source areas supply a large quantity of debris, which becomes the medial moraine due to squeezing by the ice bodies.

The crest of the cross-profile is located on the clean part of the glacier, which is about 100 m from the edge of the debris-covered part. The cleanest ice constitutes this crest, which also coincides generally with the ogive crests. The cleanest ice body comes directly from the Northern Icefield through the icefall, the part where debris-cover is least and probably albedo is high (Fisher, 1962). The debris-covered part is generally lower than the clean part when the cross-profile is taken perpendicular to the general flow direction. Ice from the icefall in the B-1 area is not as debris-free as the big one because of its small size, and its surface is not sticking out, but rather is a depression between the thick medial and lateral moraines. The white ice body disappears about half-way down owing to cover by ablation till.

4. Ogives

The arcuate pattern of the ogives is very well recognized around the middle part of the glacier. From the base of the large icefall to the first clearly-recognizable band ogive, there is a series of wave ogives. Ogives become indistinct and spacing becomes narrower as the glacier flows down and finally they become totally obscure at about 1.4 km from the snout due to stagnation. Between the first distinctive ogive and the last barely recognizable one, there are 32 ogives. This stretch covers about 5.1 km. The distance between two ogives can be taken as equivalent to the distance ice moved in a year at that point in a stable glacier (Paterson, 1981). If it takes 32 years to cover 5.1 km, the average annual flow speed would be about 160 m.

Four sets of band and wave ogives can be recognized on Soler Glacier. They appear on bodies of A-1, B-1, B-2 and B-3, originating from either below an icefall or an avalanche fan (King and Lewis, 1961). Although ice body from A-2 area does not have clear ogives, there are two dark and one white narrow bands. Since this ice body is very heavily crevassed, ogive patterns may have been obscured.

Ice body coming through the major icefall (A-1) has very distinctive band ogives at the middle stretch. About 10 of these can be clearly recognized on the vertical and oblique aerial photographs. The width of the white bands is about 60–70 m, whereas that of the dark bands is about 150–200 m. They are arcuate down-glacier. Below the icefall is a series of wave ogives, with their creat spacing about 40–50 m. There is a gap about 1 km long between the last clearly recognizable wave ogive and the first band ogive. On this ice body, there is a white lane higher than the flanking sides between 4.5 km and 1.5 km from the snout.

The ice body from B-3 is fed with avalanching only and from 1.1 km down from the avalanche fan, band ogives appear. Above the first band ogive is a series of short wave ogives continuing into the B-2 body. Band ogives are best developed on this ice body. They can be traced all the way down to a point 1.4 km from the snout. A first sight, ogives on this body appear to merge into those on the A-1 body; however, close examination has revealed that they are slightly offset near the middle part of the glacier.

Ogives on the B-2 body start from a small icefall and an avalanche fan. Just below the avalanche fan stretching from the icefall is a series of blocky crevasses. Here the glacier surface is cascading and crevasses perpendicular to the flow direction, with flat-topped ice blocks between them, run parallel to each other. Below this crevasse zone are wave ogives, spaced around 50 m apart. Some waves run into the B-3 body. Band ogives start about 600 m below the crevasse zone; only six can be recognized. There are very distinctive offsets and separation from the ogives on the B-3 body.

The icefall feeding the B-1 body has very distinctive wave ogives. They consist of broad, crescent-shaped white rises and intervening troughs. The spacing of the wave is approximately 150 m. At the apex of the trough, there is a dirt (debris) pool and these dirt pools are connected by supraglacial channels, making a beaded pattern. Band ogives are conspicuous on the debris-covered part of the body, where ice supply is supplemented by avalanching. Altogether six band ogives can be recognized.

Since the ogives on the B-3 body are very well developed, the spacings of the paired white and dark bands were measured and plotted against the distance from the snout. Although there is a definite trend in the spacing, variation becomes very large down-glacier. In order to smooth out the data, moving averages of three points were taken and plotted (Fig. 3). A reasonably good fit curve can be drawn, though with some irregularities around the 3 km point. From this figure, it can be seen that near the snout, the flow is about 100 m/year, whereas near the icefall, it is about 350 m/year. Since we measured flow rates at several points in the field (Report 10), these data were plotted on the figure, by multiplying the average daily flow rate by 365. Seasonal variation of the flow rate of temperate glaciers is considerable (ELLISTON, 1962), and the basal sliding during the summer season contributes to

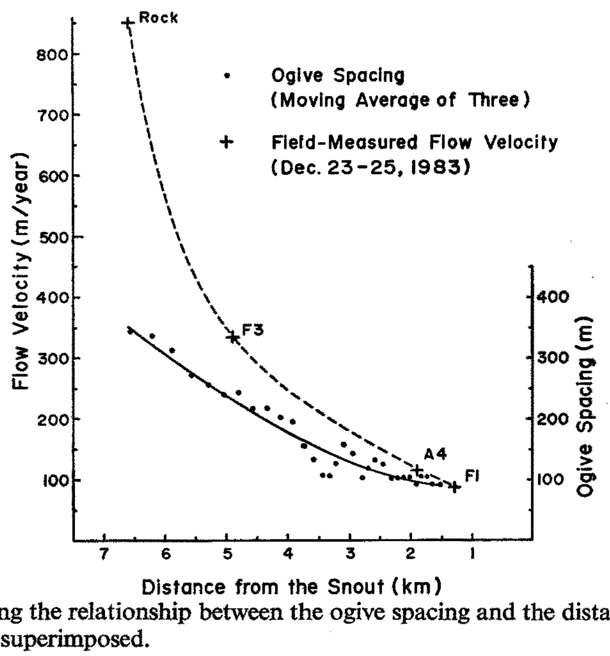

Fig. 3. Graph showing the relationship between the ogive spacing and the distance from the snout. Field-measured data superimposed.

the flow. Therefore it is very reasonable to find that the field-measured values are generally larger than the ogive spacings and data at points F1, A4 and F3 are in close agreement with those deduced from the ogive spacings. However, a large discrepancy is present at the point called "Rock", in which the field-measured value is more than double the ogive spacing.

5. Crevasses

Numerous crevasses are distributed over almost the whole area of the glacier. They can be classified into three types. The first type is observed below the base of icefall B-2. They are formed by the stress caused by a sharp change in the surface slope. The second type is found along the left and right margins of the glacier. Most of them run obliquely from the side toward the middle and up-glacier, and slightly convex down-ward. This pattern indicates the typical condition of glacier dynamics due to the effects of shear stress exerted by the valley walls as well as compressive stress along the flow (NYE, 1952). The third type shows heavily undulating surface like "seracs", which are prominent in the southern half of the glacier near the snout. In the vicinity of the snout, ice bodies are not so active but rather stagnant, and these seracs are considered to relics of old crevasses formed in the upper region and then deformed by the melting of ice walls of crevasses. Some crevasses are filled with water in the summer season. A number of water streams, water-filled pits and moulins are also located all over the glacier surface.

6. Morphology of longitudinal and cross profiles

A longitudinal profile was constructed from the 1:50,000 topographic map along the white lane of the glacier (Fig. 4). The average gradient from 1 km to 6.5 km from the snout was computed as 2.7 degrees, although the profile had a break near the middle. At this break, about 4 km from the snout, where the flow direction changes slightly from SE to ESE and the white lane is most prominent, the gradient is steepest at 3.6 degrees. Around this point, the spacing of the ogives also changes.

The morphology of the cross-section was analyzed using a curve fitting method (ANIYA and WELCH, 1981). It has long been established that the cross-section of a glacial valley can be well approximated by parabolic curves whose general equation is $Z = aX^b$, where Z is the height and X is the horizontal distance from a datum, and a and b are coefficient and exponent, respectively, determined by the least square method. In the curve fitting procedure, the ice thickness was also estimated. Using the 1:50,000 topograhic map "Cerro Hyades", cross-sections A and B were taken, by reading Z (elevation) every 100 m (X) from an origin along each of two lines 50 m apart. Next, for each half of the cross-section, the least square computation was carried out using the Z data representing the rocky side walls, by shifting the origin of the coordinate. The origin at which the standard error of estimate becomes a minimum for both sides of the cross-section was taken as final and the curve was determined. The thickness was estimated by taking the difference between the measured surface height and the base height for curve fitting. Figure 5 shows the results of curve fitting. The cross-section A is approximated by a semi-cubic parabola ($b \simeq 1.5$) on the north side and a true parabola ($b \simeq 2$) on the south side, with an estimated base height of 370 m. The standard error of estimate for the north side is 12 m and that for the south side is 17 m. Since the elevation of the glacier surface at cross-section A is about 660 m, the ice thickness is about 290 m, or on the order of

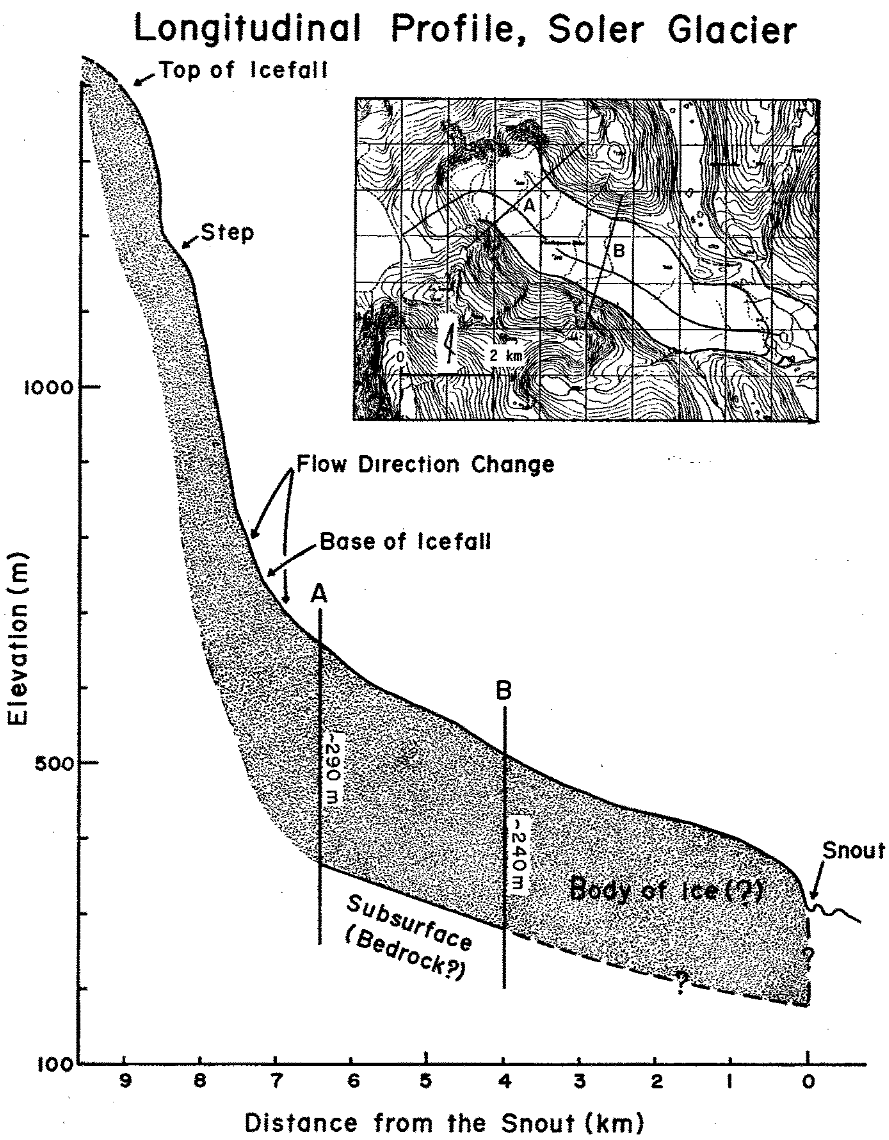

Fig. 4. Longitudinal profile between the top of the big icefall and the snout, also indicating the positions of the two cross-sections and the inferred subsurface.

300 m. The morphology of cross-section B is quite different. With the estimated base height of 290 m, the side was approximated by a quartic parabola ($b \simeq 4$), and the south side by an almost straight line ($b \simeq 1$). The standard error of estimate is 13 m for the north side and 22 m for the south side. At this cross-section the estimated ice thickness is about 240 m.

7. Summary and conclusions

The structure and morphology of Soler Glacier were examined utilizing vertical aerial photographs. Detailed mapping of the surface revealed that the glacier had five drainage areas and

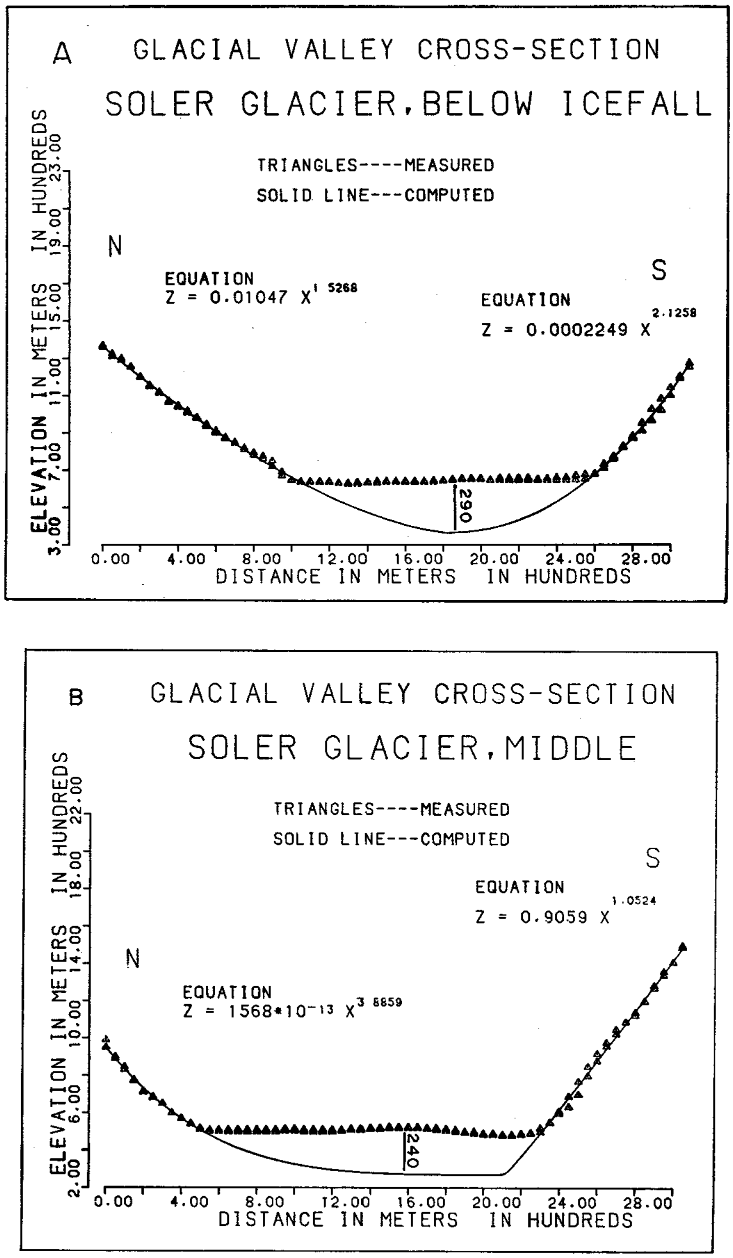

Fig. 5. Approximation of the cross-valley morphology and estimation of the thickness.

corresponding ice bodies. The total drainage area is estimated to be about 44 km², with the icefield contributing 36 km², and the Mt. Hyades slope 8 km². The surface consists of two distinctive bodies: the northern half with debris cover and the southern half with clean ice.

There are two conspicuous ogive patterns on the surface, although close examination of aerial photographs indicate that one seemingly-uniform ogive pattern actually consists of three separate ones. Thirty-two band ogives were counted in a 5.1 km distance, giving an average annual flow rate of 160 m. Ogive spacings were plotted against distance from the snout and compared with field data. The agreement is very reasonable.

Three types of crevasses were recognized: 1) one type resulting from the change in the surface slope, located below an icefall; 2) one type found along glacier margin, caused by shear stress; and 3) seracs located near the snout.

Analysis of the longitudinal morphology has revealed that there is a break near the 4 km point from the snout, at which the flow direction changes and ogive spacing also changes. Morphology of the cross-section was analyzed using the model $Z = aX^b$. The exponent b ranges from almost one to four. The ice is about 300 m thick below the icefalls, and about 240 m near the break point in the longitudinal profile.

References

ANIYA, M. and WELCH, R. (1981): Morphological analyses of glacial valleys and estimates of sediment thickness on the valley floor: Victoria Valley System, Antarctica. Antarctic Record, **71**, 76–95.

ELLISTON, G. R. (1962): Seasonal changes of speed in temperate valley glaciers. Journal of Glaciology, **4**, 289.

FISHER, J. E. (1962): Ogives of the Forbes type on Alpine glaciers and a study of their origin. Journal of Glaciology, **4**, 53–61.

KING, C. A. M. and LEWIS, W. V. (1961): A tentative theory of ogive formation. Journal of Glaciology, **3**, 913–939.

NYE, J. F. (1952): The mechanics of glacier flow. Journal of Glaciology, **2**, 82–93.

PATERSON, W. S. B. (1981): The Physics of Glaciers, 2nd Ed. Pergamon Press, Oxford. 380 p.

Resumen. Estructura y morfología del Glaciar Soler

El Glaciar Soler es un glaciar temperado y de valle, teniendo su área de ablación cerca de 7 km de largo y 1,5 km de ancho en promedio, con un área actual de 11,7 km^2. En términos de superficie, cerca del 50% del hielo actualmente proviene del Campo de Hielo Norte, mientras que el resto proviene de la falda sureste del Cerro Hyades. El área de acumulación del glaciar se estimó en 24 km^2 (Campo de Hielo, 16 km^2; Cerro Hyades, 8 km^2), desde donde el hielo cae a través de saltos de hielo y avalanchas. El análisis estereoscópico de las fotos aéreas verticales reveló que hay cinco cuerpos de hielo separados, distinguidos por el diseño de ojivas y la morfología de la superficie del glaciar (Fig. 1).

Se mapeó estructuras de superficie en detalle usando las fotos aéreas verticales (Fig. 2). Se distinguen claramente dos cuerpos de hielo separados. La mitad norte del glaciar que está alimentada de hielo proveniente del Cerro Hyades está cubierta por detritos (B1, B2 y B3), mieitras que la mitad sur consiste en hielo limpio que es descargado desde el Campo de Hielo (A1 y A2).

Hay dos tipos de ojivas, de onda y de banda. En el cuerpo de hielo norte (B1), hay una serie de ojivas de onda ubicadas entre el tercio inferior del salto de hielo y el área donde la superficie se torna casi plana. Con respecto a ojivas de banda, se reconoció un total de 32 bandas en el cuerpo de hielo A1 y B3 desde la base del salto de hielo hasta 1,4 km del frente actual. Si toma 32 años cubrir esta distancia, cerca de 5,1 km, la velocidad media anual sería de 160 m. Siendo que las ojivas en el cuerpo B3 están bien desarrolladas, el espaciamiento entre pares de bandas fue medido y dibujado versus la distancia desde el frente (Fig 3). A partir de

esto, se obtiene que la velocidad de flujo cerca del frente es alrededor de 100 m/a, mientras que alcanza 350 m/a cerca del salto de hielo. Esto está bastante de acuerdo con los datos de terreno medidos en Diciembre de 1983 (ver Reporte 10).

Numerosas grietas fueron claramente visibles, especialmente en la parte sur del glaciar (Fig. 2). Muchas de las grietas principales corren en forma oblicua hacia el lado derecho del glaciar y muestran una forma ligeramente convexa en el sentido del flujo. Este modelo indica tal condición dinámica como efecto de la fricción de las paredes del valle, así como la compresión longitudinal del glaciar.

El perfil longitudinal (Fig. 4) construido a partir de la carta topográfica 1:50.000 indica que la pendiente media entre 1 km y 6,5 km del frente es de 2,7 grados. La morfología de la sección transversal del valle fue analizada utilizando un modelo $z = ax^b$, donde z es la altura, x la distancia desde el punto origen; a y b son el coeficiente y el exponente respectivamente, determinados por el método de mínimos cuadrados. La Fig. 5 muestra el resultado del ajuste de curvas. El espesor del hielo fur también estimado usando el mismo modelo: era del orden de los 300 m en la sección A y cerca de 240 m en la sección B.