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Utilization of 6 × 6 cm format vertical aerial photographs for repetitive mapping of surface morphology and measurement of flow velocities of a small glacier in a remote area: Glaciar Soler, Hielo Patagónico Norte, Chile

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ABSTRACT. Using vertical aerial photographs taken manually with a 6 × 6 cm format camera in 1984, 1986 and 1999, the surface morphology of the ablation area of Glaciar Soler, Hielo Patagónico Norte (northern Patagonia icefield), Chile, was studied. Glaciar Soler has an area of 50.9 km^2; the ablation area below the icefall is about 7 km long and 2 km wide. An uncontrolled aerial-photographic mosaic for the area below the icefall was assembled from 40–60 aerial photographs, on which the surface morphology was mapped from interpretation of stereo pairs of the enlarged photographs (scales of 1:4500 to 1:8000). The mapped features include debris-free and debris-covered ices, ogive bands and waves, crevasses, supraglacial streams, moulins, medial moraines, troughs and grooves. A total of 32–34 pairs of ogive bands were recognized, from which an average flow velocity of about 160 m a^{-1} was deduced. The spacing of a pair of light and dark ogive bands indicates that the flow velocity ranges from about 350 m a^{-1} near the icefall to some 100 m a^{-1} near the snout. Comparison of the field-measured data with the ogive spacing indicates that the seasonal variation in flow velocity of Glaciar Soler is very large, probably because of variation in the amount of basal sliding.

INTRODUCTION

In recent years, satellite remote sensing has increasingly been applied to various glaciological studies, using a variety of satellite platforms and sensors, including those with improved spatial, spectral, radiometric and temporal resolutions. The advantages of satellite remote sensing include periodic and large area coverage under the uniform condition. Because the swath widths are at least 60 km, satellite data are best suited for studying large to medium-sized glaciers with areas exceeding a few hundred km^2. For small glaciers, conventional aerial photographs are still an important source of remotely sensed data, the coverage of which can be easily varied by changing the flying height and/or focal length of a camera lens.

In remote areas, a metric camera and a light aircraft able to accommodate it are often not available. Hielo Patagónico Norte (the northern Patagonia icefield) is such an area. Aerial photographs taken by the U.S., Chilean and Argentine governments between the 1960s and 1980s, with scales of about 1:70 000 to 1:80 000, cover the area. These photographs are generally still of a scale too small for the examination of glaciers < 50 km^2. For such small glaciers, near-vertical aerial photographs taken with a 6 × 6 cm format camera are easy to acquire, because a hand-held camera is simple to operate and economical to use (Aniya and Naruse, 1985, 1986, 1987). Also an opening in the aircraft fuselage can be made inexpensively, without the need for substantial structural modification.

The purpose of this study is to analyze morphological changes on the surface of Glaciar Soler, Chile, based on the morphological maps produced from mosaics of 6 × 6 cm aerial photographs taken in 1984, 1986 and 1999.

STUDY AREA

The northern and southern Patagonia icefields are located in the southern part of South America, between 46°30′ and 51°30′ S along longitude 73°30′ W, extending for 550 km along the axis of the Andes, with widths of about 8–45 km. The two icefields, Hielo Patagónico Norte (HPN; northern Patagonia icefield; 4200 km^2) and Hielo Patagónico Sur (HPS; southern Patagonia icefield; 13 000 km^2) are the largest temperate glaciers in the Southern Hemisphere, with a total combined area of 17 200 km^2. HPN has 28 outlet glaciers (Aniya, 1988, fig. 1) flowing out from the margin of the icefield. In the past we have carried out extensive fieldwork in HPN, in particular at Glaciares Soler and San Rafael in 1984–86 (Nakajima, 1985, 1987) and in 1998 (Aniya and Naruse, 2001). As part of these projects, Aniya acquired vertical aerial photographs over Glaciar Soler in 1984, 1986 and 1999 (Aniya, 1985, 1987, 2000).

Glaciar Soler is located at 46°54′ S, 73°11′W, on the east side of HPN (Fig. 1). It is a small glacier with a total area of 50.9 km^2 and a length of 16.6 km. The elevation ranges from 3078 m (top of Cerro Hyades) to about 350 m, but much of the accumulation area in the icefield lies at 2000–2200 m. The accumulation–area ratio (AAR) is 0.73, with the equi-

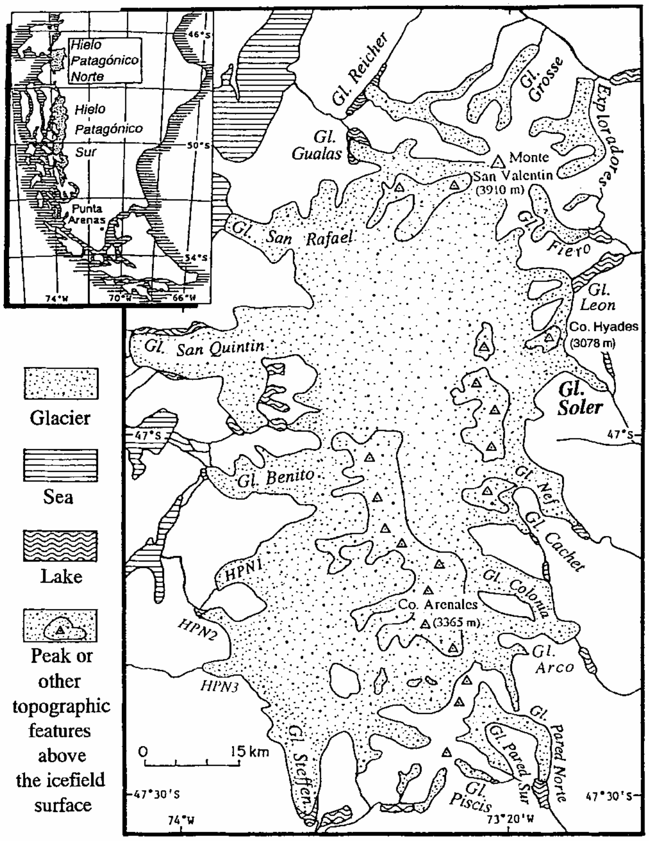

Fig. 1. The study area: Glaciar Soler and HPN.

librium-line altitude (ELA) located around 1350 m (Aniya and Naruse, 1987). From estimation of the ELA in the field in 1985 (Cassasa, 1987), and interpretation of vertical aerial photographs taken in 1975, the AAR was estimated (Aniya and Naruse, 1987). Because of subsequent rapid recession, the ELA may have lowered and the AAR may have become smaller, but we do not have the new estimates. The ablation area lies mostly below icefalls, from 850 m elevation down, with an area of 14.5 km^2, a length of about 7 km and a width of about 2 km. The ablation area consists of two distinct ice bodies, debris-free and debris-covered. The debris-free part, which is fed with ice from the icefield, is composed of two different sections, while the debris-covered part, which is fed by ice avalanches from the flank of Cerro Hyades, contains five different sections (Aniya and others, 1988; Fig. 2 inset).

The glacier has been retreating, and between 1986 and 1999 part of the snout retreated about 200–500 m (Aniya, 2001). The retreat has been accompanied by considerable thinning, averaging 5.2 m a^{-1} for 1983–85 and 3.2 m a^{-1} for 1985–98 at 0.5–2.5 km from the snout (Naruse and others, 2000). Consequently, two proglacial lakes have formed, though calving is not yet active.

AERIAL-PHOTOGRAPHIC SURVEY OPERATIONS

In order to study the morphology of Glaciar Soler, we flew over the ablation area of the glacier in January 1984, November 1986 and November 1999. The camera used was a Zenza Bronica SQ-Am with a format of 6 × 6 cm, equipped with an 80, 100 or 110 mm lens. The film used was Kodak Ektachrome Professional EPD 220 Reversal (ASA 200 for 1984, and 64 for 1986) and ENP 220 Reversal (ASA 100 for 1999). The aircraft employed were a Cessna 182 in 1984 and 1986, and a Piper Seneca in 1999. A small hole of about 15 cm diameter was cut through the fuselage under the co-pilot's seat. The camera was placed in the opening and held by hand. Using a gridded focusing screen, photographs were taken manually so that forward overlap was > 50% to achieve complete stereoscopic coverage. The flying height was about 3200 m a.s.l. in 1984 and 3000 m a.s.l. in 1986 in order to avoid Cerro Hyades (3078 m), which looms above the head of the ablation area. In 1999, however, it was about 2500 m a.s.l. due to low cloud ceiling, which forced us to miss the icefall area of the mountainside.

SURFACE MORPHOLOGY

The uncontrolled aerial-photographic mosaic of Glaciar Soler was assembled from 40–60 aerial photographs acquired each year for mapping morphology (Fig. 2). The approximate scale was determined using a 1 : 50 000 scale topographic map published by Instituto Geográfico Militar of Chile. Because of the uncontrolled nature of the mosaic, all distance measurements are approximate, with an estimated error of up to 10%.

The 6 × 6 cm quasi-vertical aerial photographs were enlarged to 24 × 24 cm (scales of roughly 1 : 4500 for 1999 and 1 : 8000 for 1984) for detailed stereoscopic interpretation. The mapped features include debris-covered and debris-free glacier surfaces, medial moraines, band ogives, wave ogives, major individual crevasses, general crevasse patterns, supraglacial streams and ponds, and ice-cored moraines. Special features are depressions, grooves, troughs, moulins and debris mounds for 1984, 1986 and/or 1999 maps. Grooves are wide U-shaped troughs which have developed nearly perpendicular to the crevasses on the right margin of the middle reach of the glacier.

Morphological changes

Between 1984 and 1986, the most notable change in the surface morphology was the formation of thrust-moraine ridges located across the glacier about 1 km from the snout (Fig. 2b). They were covered by rounded sand. Since then, this part of the glacier has become a proglacial lake, with residuals of the thrust moraines bordering the lower end of the lake. The formation of a proglacial lake in front of the debris-covered glacier ice (north or lefthand side) is a notable change between 1986 and 1999. From the aerial-photographic survey it was inferred that the lake was formed around 1991–92 (Aniya, 1992; Wada and Aniya, 1995). The proglacial lake on the south (righthand) side of the snout has grown considerably since 1986.

On the 1999 map (Fig. 2c), there is a semicircular debris-covered ice feature, part of which stands out slightly from the surrounding ice, on the righthand side of the snout (Fig. 3). When Aniya visited here in November 1995, it was a depression a few hundred meters in diameter, with 10–15 m deep cliffs. There was a channel (or narrow proglacial lake) between the depression and the valley wall. The edge of the depression on the valley-wall side was then covered by a large volume of rock-avalanche debris on which some vegetation survived. On the valley wall there was a fresh scar of a landslide (or rock avalanche). According to a local guide, a flood had occurred in May 1994 in Río Cacho. Indeed, the area immediately below the snout had been scoured up to several meters above the normal river level.

From the above information, the event that occurred is

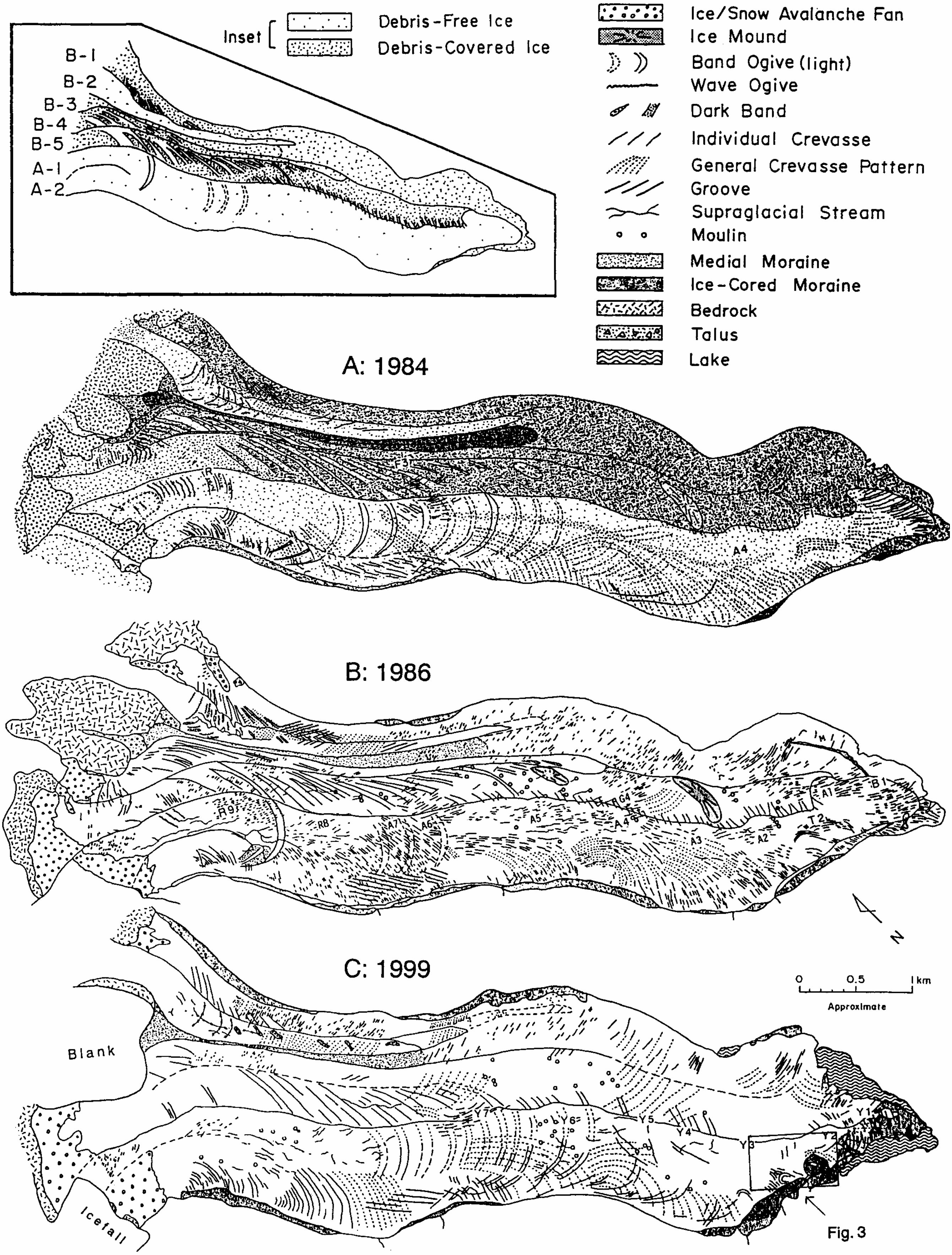

Fig. 2. Surface morphology maps: A, 1984 (after Aniya and Naruse, 1985); B, 1986 (after Aniya and others, 1988); and C, 1999 (extent of Fig. 3 indicated). Inset map is based on the 1986 map, showing the debris-free and debris-covered bodies and glacier sections.

interpreted as follows. It is assumed that there was a subglacial cave below the depression since on the 1993 oblique aerial photographs taken by Aniya there was a trace of the circular depression. The cave may have been formed on the lee side of a large protruding bedrock hump. Probably it was in the process of subsidence. Then a rock avalanche slid into the proglacial lake and onto the glacier surface; a large volume of water was displaced, removing the pressure that

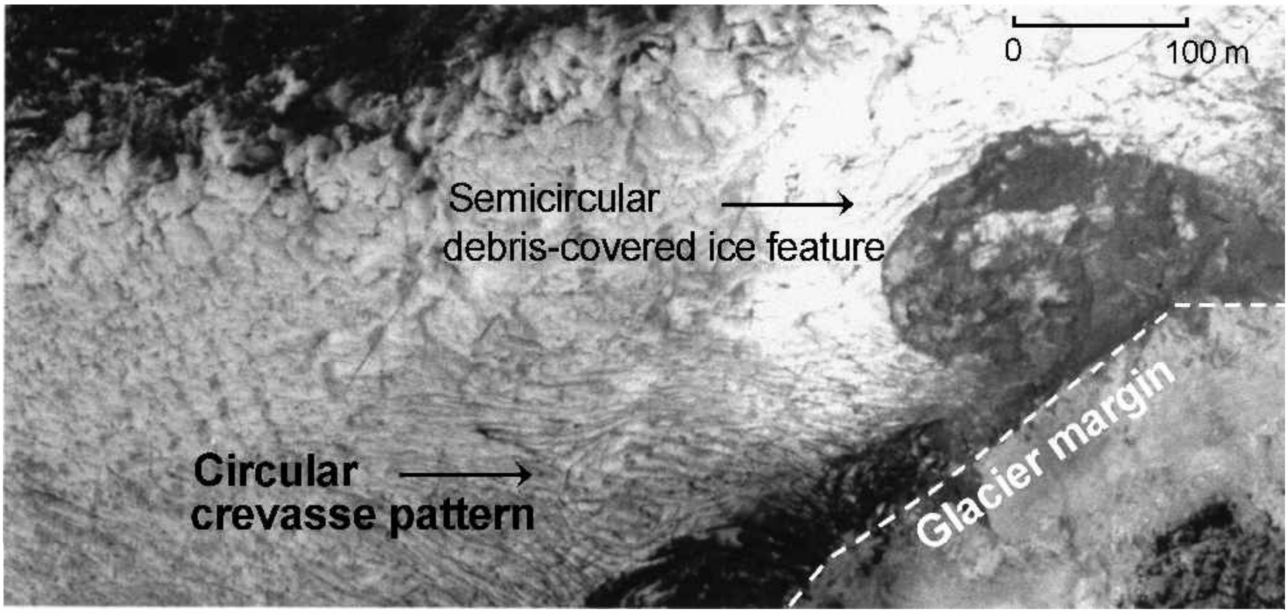

Fig. 3. Semicircular debris-covered surface and circular crevasse pattern on the southern (righthand) margin of the glacier, about 1.4 km from the snout (photo taken by Aniya on 29 November 1999).

supported the ice above, and the surface collapsed, in turn displacing another large volume of water.

Ogives

Of the seven surface ice-flow features of the ablation area, all of which are fed through an icefall or by avalanches, wave ogives develop only on the B2 feature, while band ogives develop on the B1, B4, B5 and A1 features (Fig. 2 inset; Aniya and others, 1988). Among these band ogives, those that developed on the B5 feature are most distinctive, followed by those developed on the A1 feature. Band ogives developed on the B5 and A1 features were delineated and marked on the mosaic, and the width of a pair of dark and light bands was measured at the contact of the B5 and A1 features. Between 1984 and 1999, the retreat of the snout is substantial, so the distance was measured from the base of the large icefall (A1 feature) for comparison, rather than from the snout.

In 1986, development of aerial photographs that covered the middle part of the A1 and A2 features revealed that neither the light ogive bands nor the individual crevasses could be identified. However, light ogive bands were observed on the B5 feature, and the measurements were performed there.

On the 1999 mosaic, light ogive bands have become obscure on all the ice-flow features. Wave ogives on the B2 feature have also become less distinctive. The distinction between the B4 and B5 features has become less clear because of poor development of light ogive bands on the B4 feature. Although debris-covered, the surface of the B4 and B5 features is flat and smooth, unlike that of the B1, B2 and B3 features which is quite rough because of a thick debris cover. Light ogive bands developed on the B5 feature are recognizable about halfway down the icefall, but farther down they become indistinct. Those on the A1 feature have also become much less distinct, and few of the arcuate light bands could be identified. Consequently, the moving average of the width could not be plotted for many of the ogives, and a dummy figure had to be employed. The poor recognition of light ogive bands in the upper part of the ablation area may be attributed to the increased exposure of bedrock in the icefall. This causes an increase in the supply of supraglacial debris, which, combined with thinning of ice in the lower half of the glacier, leads to greater accumulation of debris on the surface.

The width of a pair of light and dark ogive bands can be taken as the annual flow velocity at that point in a stable glacier (King and Lewis, 1961; Haefeli, 1966; Aniya and Naruse, 1987). Although Glaciar Soler has been retreating, the width–velocity relationship may be taken as roughly true for the study period. Figure 4 show plots of the ogive band spacing and the estimated annual flow velocity from the field measurements, with the distance from the base of the large icefall. The flow velocity was measured in the field during the periods 23–25 December 1983, 21 October–18 November 1985 and 15 November–10 December 1998; the daily average was calculated from these measurements. The estimated annual flow velocity was obtained by simply multiplying the daily average by 365. Although the field measurements were carried out 1 year earlier for the 1999 ogive spacing, it is assumed that there were no substantial differences. Each year, variation patterns of the ogive spacing and field-measured flow velocities are similar, although in 1984 and 1998/99 field-measured flow velocities were greater than the ogive spacing, while in 1986 ogive spacing was greater than the field-measured flow velocity. This is attributed to the different dates used for the measurement periods, and the likelihood that the amount of subglacial water was different (Aniya and others, 1988). Indeed, the field-measured flow velocity increased from October to December, i.e. from spring to summer, although the ogive spacings are more or less similar in the three periods. At Glaciar Soler, the contribution of the basal sliding, which is largely controlled by the amount of subglacial water and development of a complex subglacial stream network at the glacier/bedrock interface, to the flow velocity is estimated to be nearly two-thirds (Naruse and others, 1992). The large seasonal variation in flow velocity at Glaciar Soler strongly contrasts with the flow-velocity variation of Glaciar Perito Moreno, HPS, where seasonal variation is small (Naruse and Skvarca, 2000). Because Glaciar

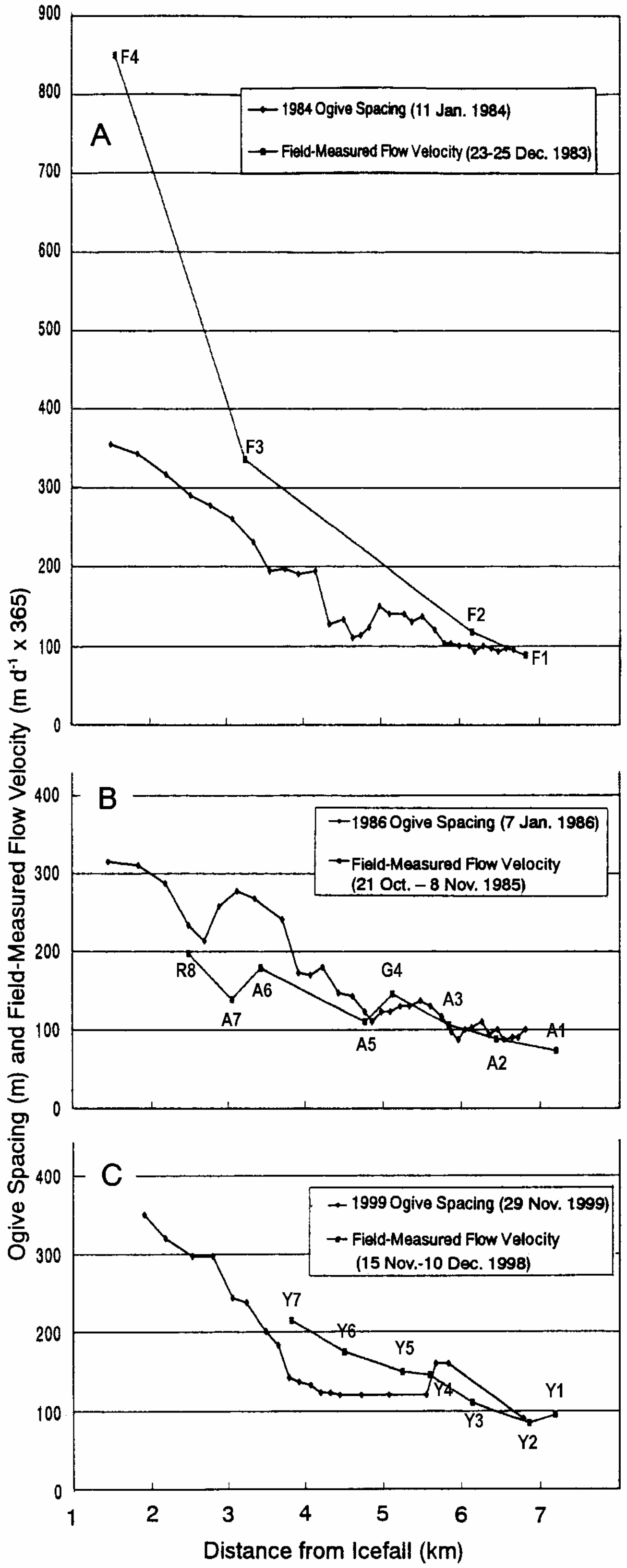

Fig. 4. Plots of ogive band spacing and field-measured flow speed.

Soler terminates on land, while Glaciar Perito Moreno calves into a lake, the condition of the snout probably accounts for the difference in flow-velocity variations.

The number of pairs of ogive bands recognized on the 1984 aerial photographs is 32; for 1986 it is 34. In 1999, only 20 pairs could be recognized. From these sets of aerial photographs an average flow velocity of about 160 m a^{-1} is calculated for the ablation area. According to the ogive spacing, the flow velocity ranges from about 350 m a^{-1} near the icefall to some 100 m a^{-1} near the snout. Comparison of flow-velocity distributions during these three periods reveals that variations in flow velocity in 1984 and 1999 are rather similar, and unlike those in 1986. In 1984 and 1999, the flow velocity decreased fairly regularly downstream, while in 1986 it varied considerably near the middle of the glacier. The flow-velocity pattern in 1986 (Fig. 4b) was compared with the inferred bedrock profile (Casassa, 1987; Aniya and others, 1988; Fig. 5). About 3.5 km from the icefall, flow velocity increased in both ogive-spacing and field-measured data. In the bedrock profile there is a rise of about 3.5 km from the icefall, and measurement point A6 is located at the top of the subglacial rise. It can be inferred that the irregular flow-velocity pattern around 3–4 km from the icefall was caused by compressing and extending flows that reflect the bedrock profile. The increase in the ogive spacing near the snout in 1999 could be due to errors in delineation of light bands, which are very obscure.

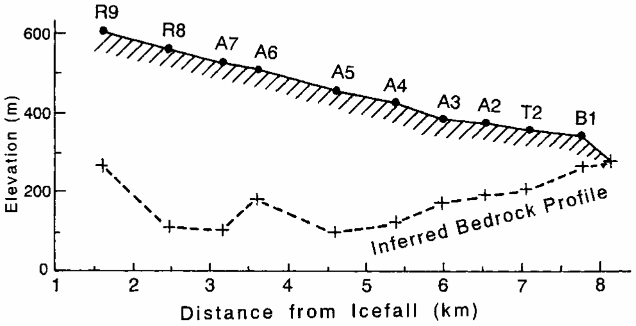

Fig. 5. Inferred subglacial topography along the border between the B5 and A1 features, where the ogive band spacing was measured (after Aniya and others, 1988).

Crevasse pattern

On the 1999 aerial-photographic mosaic, there is an interesting crevasse pattern near the semicircular debris-covered ice feature located by the proglacial lake on the south (righthand) side of the snout (Fig. 3). Its pattern is circular, with a convoluted upstream end, suggesting a complicated flow regime, probably caused by subglacial topography.

Otherwise, no significant changes in crevasse patterns were recognized between 1984 and 1999. Notable features are splaying crevasses, which can be clearly observed near the southern margin of the middle reach of the glacier. The crevasses meet the margin at angles of about 45°. They are curved up-valley towards the center line and are aligned roughly parallel to the flow direction near the center line. They are formed by composition of shear stress due to lateral drag and longitudinal compressive stress (Nye, 1952). This stress field is verified from flow measurements in December 1998 (Yamaguchi, 2000), in which flow velocity decreased monotonically from 0.59 m d^{-1} (215 m a^{-1}) at Y7 to 0.3 m d^{-1} (110 m a^{-1}) at Y3 (see Fig. 3c), which corresponds to a compressive strain rate of -0.04 a^{-1}.

Harper and others (1998) concluded from an analysis of crevasse patterns at Worthington Glacier, Alaska, U.S.A., that the splaying and transverse crevasses are translated by the flow from several tens of meters to 100 m, and last no more than 1–2 years. On Glaciar Soler, most of the old, inactive crevasses have quickly disappeared after moving only a few hundred meters due mainly to the high rate of surface melting. This may be a reason why there are no clear crevasses except in the marginal areas of the middle and lower reaches of the ablation area.

Surface lowering

In general, surface lowering between 1984 and 1999 is notable everywhere. Naruse and others (2000) reported that between 1985 and 1998 the mean thinning of the surface of the lower half of the ablation area was 42 ± 5 m. The debris-covered part of the B1 feature along the valley wall has since become an ice-cored moraine, the result of the surface lowering. The white ice of the B2 feature has become shorter by about 400 m between 1984 and 1999. The wave ogives developed here have become less pronounced, with a diminished amplitude. The B3 feature, a medial moraine, has also become shorter by about 500 m.

CONCLUDING REMARKS

Using uncontrolled aerial-photographic mosaics of Glaciar Soler, which were produced from 6 × 6 cm quasi-vertical aerial photographs taken manually from small aircraft in 1984, 1986 and 1999, the surface morphology and changes over time were analyzed, thereby demonstrating the advantage of using such photographs for studies of small glaciers. From the number of ogive bands, the average flow velocity was deduced to be about 160 $\mathrm{m\,a^{-1}}$ for the ablation area, and from the ogive-band spacing a flow velocity ranging from about 350 to 100 $\mathrm{m\,a^{-1}}$ was deduced. Comparison with estimates from short-term field measurements (daily mean multiplied by 365) indicates that the seasonal variation in flow velocity is large, probably due to variation in the amount of basal sliding, and care must be taken when extrapolating these values into annual values.

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REFERENCES

Aniya, M. 1985. Aerial photographic surveys over Soler, Nef and San Rafael Glaciers. *In* Nakajima, C., *ed. Glaciological studies in Patagonia Northern Icefield, 1983–1984.* Nagoya, Japanese Society of Snow and Ice. Data Center for Glacier Research, 88–93.

Aniya, M. 1987. Aerial surveys over the Patagonia Icefields. *Bull. Glacier Res.* 4, 157–161.

Aniya, M. 1988. Glacier inventory for the Northern Patagonia Icefield, Chile, and variations 1944/45 to 1985/86. *Arct. Alp. Res.*, **20**(2), 179–187.

Aniya, M. 1992. Glacier variation in the Northern Patagonia Icefield, Chile, between 1985/86 and 1990/91. *Bull. Glacier Res.* 10, 83–90.

Aniya, M. 2000. [Aerial surveys of outlet glaciers of Hielo Patagónico Norte in 1998 and 1999.] *In* Aniya, M., *ed. Holocene glacier variations and their mechanisms in Patagonia, South America.* Ibaraki, University of Tsukuba. Institute of Geoscience, 30–39. [In Japanese.]

Aniya, M. 2001. Glacier variations of Hielo Patagónico Norte, Chilean Patagonia, since 1944/45, with special reference to variations between 1995/96 and 1999/2000. *Bull. Glaciol. Res.* 18, 55–63.

Aniya, M. and R. Naruse. 1985. Structure and morphology of Soler Glacier. *In* Nakajima, C., *ed. Glaciological studies in Patagonia Northern Icefield, 1983–1984.* Nagoya, Japanese Society of Snow and Ice. Data Center for Glacier Research, 70–79.

Aniya, M. and R. Naruse. 1986. Mapping structure and morphology of Soler Glacier, in northern Patagonia, Chile, using near-vertical, aerial photographs, taken with a non-metric 6 × 6 cm-format camera. *Ann. Glaciol.*, **8**, 8–10.

Aniya, M. and R. Naruse. 1987. Structural and morphological characteristics of Soler Glacier, Patagonia. *Bull. Glacier Res.* 4, 69–77.

Aniya, M. and R. Naruse. 2001. Overview of glaciological research project in Patagonia in 1998 and 1999: Holocene glacier variations and their mechanisms. *Bull. Glaciol. Res.* 18, 71–78.

Aniya, M., G. Casassa and R. Naruse. 1988. Morphology, surface characteristics and flow velocity of Soler Glacier, Patagonia. *Arct. Alp. Res.*, **20**(4), 414–421.

Casassa, G. 1987. Ice thickness deduced from gravity anomalies on Soler Glacier, Nef Glacier and the Northern Patagonia Icefield. *Bull. Glacier Res.* 4, 43–57.

Haefeli, R. 1966. Some notes on glacier mapping and ice movement. *Can. J. Earth Sci.*, **3**(6), 863–876.

Harper, J. T., N. F. Humphrey and W. T. Pfeffer. 1998. Crevasse patterns and the strain-rate tensor: a high-resolution comparison. *J. Glaciol.*, **44**(146), 68–76.

King, C. A. M. and W. V. Lewis. 1961. A tentative theory of ogive formation. *J. Glaciol.*, **3**(29), 913–939/912.

Nakajima, C. 1985. *Glaciological studies in Patagonia Northern Icefield, 1983–1984.* Nagoya, Japanese Society of Snow and Ice, Data Center for Glacier Research.

Nakajima, C. 1987. Outline of the Glaciological Research Project in Patagonia, 1985–1986. *Bull. Glacier Res.* 4, 1–6.

Naruse, R. and P. Skvarca. 2000. Dynamic features of thinning and retreating Glaciar Upsala, a lacustrine calving glacier in southern Patagonia. *Arct. Antarct. Alp. Res.*, **32**(4), 485–491.

Naruse, R., H. Fukami and M. Aniya. 1992. Short-term variations in flow velocity of Glaciar Soler, Patagonia, Chile. *J. Glaciol.*, **38**(128), 152–156.

Naruse, R., S. Yamaguchi, M. Aniya, T. Matsumoto and H. Ohno. 2000. Recent thinning of Soler Glacier, northern Patagonia, South America. *Mater. Glyatsiol. Issled./Data Glaciol. Stud.* 89, 150–155.

Nye, J. F. 1952. The mechanics of glacier flow. *J. Glaciol.*, **2**(12), 82–93.

Wada, Y. and M. Aniya. 1995. Glacier variations in the northern Patagonia Icefield between 1990/91 and 1993/94. *Bull. Glacier Res.* 13, 111–119.

Yamaguchi, S. 2000. [Flow measurements of Soler Glacier, Patagonia.] *In* Aniya, M., *ed. Holocene glacier variations and their mechanisms in Patagonia, South America.* Ibaraki, University of Tsukuba. Institute of Geoscience, 47–54. [In Japanese.]