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Ice thickness deduced from gravity anomalies on Soler Glacier, Nef Glacier and the Northern Patagonia Icefield

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Abstract

Gravity measurements were carried out from October to December 1985 on Soler Glacier, Nef Glacier and over the icefield, including a 30 km long east-west traverse to San Quintín Glacier in the Northern Patagonia Icefield. In total 132 stations were occupied, 99 on ice. Bouguer anomalies were computed allowing for standard corrections, and residual anomalies were obtained by subtracting an estimated regional gradient. Talwani's (1959) 2 dimensional method was applied to seven transverse profiles resulting in maximum ice thickness values of 575 ± 85 m for Soler Glacier, 1000 ± 250 m for Nef Glacier and 1460 ± 500 m on the west part of the icefield. For stations not belonging to transverse profiles an ice thickness was calculated by extrapolating gravity factors obtained by Talwani's method.

1. Introduction

Referring to the Northern Patagonia Icefield (NPI), Brüggen (1950) wrote : "The ice fills a great longitudinal valley which separates the relatively small mountains on the coast with a range of very high peaks, the highest being San Valentín." Moreover, within the icefield, several nunataks emerge, forming secondary mountain ranges and longitudinal valleys covered with ice.

The bedrock topography and ice thickness of both the outlet glaciers and the icefield is basic information needed to understand the characteristics of the Patagonian Icefields, where to date no measurements of ice thickness have been carried out. Only an estimation of the bedrock topography at Soler Glacier by extrapolating both sides of the glacier valley had been made before (Aniya and Naruse, 1985).

From October to December, 1985, gravity measurements combined with precise triangulation of station coordinates (Naruse, 1987) were carried out in the ablation area of Soler Glacier ; and in November/December a preliminary gravity survey with altimetric readings was made on the ablation area of Nef Glacier and the icefield (accumulation areas of Nef, Soler and San Quintín glaciers), including an east-west traverse over the icefield. In addition, the location of ice divides between these glaciers were estimated.

The gravity method to estimate ice thickness was first used by Martin (1949) in the Greenland ice sheet, and later applied to a valley glacier in Norway (Bull and Hardy, 1956). This method is convenient to determine the general relief of the bedrock, because the observed gravity represents a mean value in the area around the station, thus smoothing the subglacial profile. It was used extensively in the 1960's, together, and sometimes in combination with the more precise but cumbersome seismic reflection method. Both these methods have been replaced by radio echo sounding, introduced in the late 1960's, and widely used in polar ice sheets, which has the great advantage of obtaining a continuous profile of the bed. As for accuracies of these three methods, the following figures have been suggested for Antarctica : 3 % for seismic shooting (Bentley, 1964 and Drewry, 1975) : 1.5 % for radio echo soundings (Drewry, 1975) and 7-10 % for gravity results (Tsukernik, 1962 ; Kapitsa and Sorokhtin, 1963). As pointed out by Drewry (1975) the error for gravimetric thickness may increase to 15-20 % in areas of irregular bedrock relief with poorly determined surface altitudes and big variations in subglacial rock density. But, on the other hand, in areas of very 'rough surface and/or subsurface topography, as the Yamato mountains in east Antarctica (Nagao and Yoshida, 1984) and thin valley glaciers such as Fox Glacier in Canada (Crossley and Clarke, 1970), both the seismic and radio echo sounding methods have failed due to multi-reflections and echos. Thus, the gravity survey is still a very appropriate preliminary method to estimate ice thicknesses, and has the advantage of very simple field work involved.

2. Gravity measurements

The gravity measurements were made with Worden Prospector Gravimeter N. 816 (geodetic model) which was on loan from the Instituto Antãrtico Chileno, Santiago. The calibration value of 0.0951 mgal/division supplied by the manufacturers was checked in Santiago, between International Gravity Standardization Net 1971 (IGSN 71) absolute gravity points reformed by Nakagawa *et al.* (1983), yielding no significative difference. Nevertheless, in the field tare of several miligals occurred a few times between close stations, where the gravity difference was quite small in the previous measurements. These erroneous measurements were easily recognized and eliminated. For glaciological purposes, only relative differences of gravity were measured, averaging in general several observations between stations. Also, no absolute pendulum gravity stations exist in the area.

2. 1. Soler Glacier

A total of 38 stations were occupied, of which 15 were located off the glacier. From October 23 to November 19, 1985, gravity was repeatedly measured in three transverse profiles : Lines I, T and G, and a longitudinal traverse along the centerline (Fig. 1). Each station was occupied at least three times, and the gravity differences between neighbouring stations were averaged, the error being smaller than 0.3 mgal. Naruse (1987), by precise triangulation from control points, measured the coordinates of all the gravity stations. These stations coincided with ice flow stations, the elevation error being about 0.1 m.

2. 2. Nef Glacier and icefield

On Nef Glacier one transverse line in the middle section was established, plus a longitudinal line to a point 4 km from the snout (Fig. 2). Each gravity

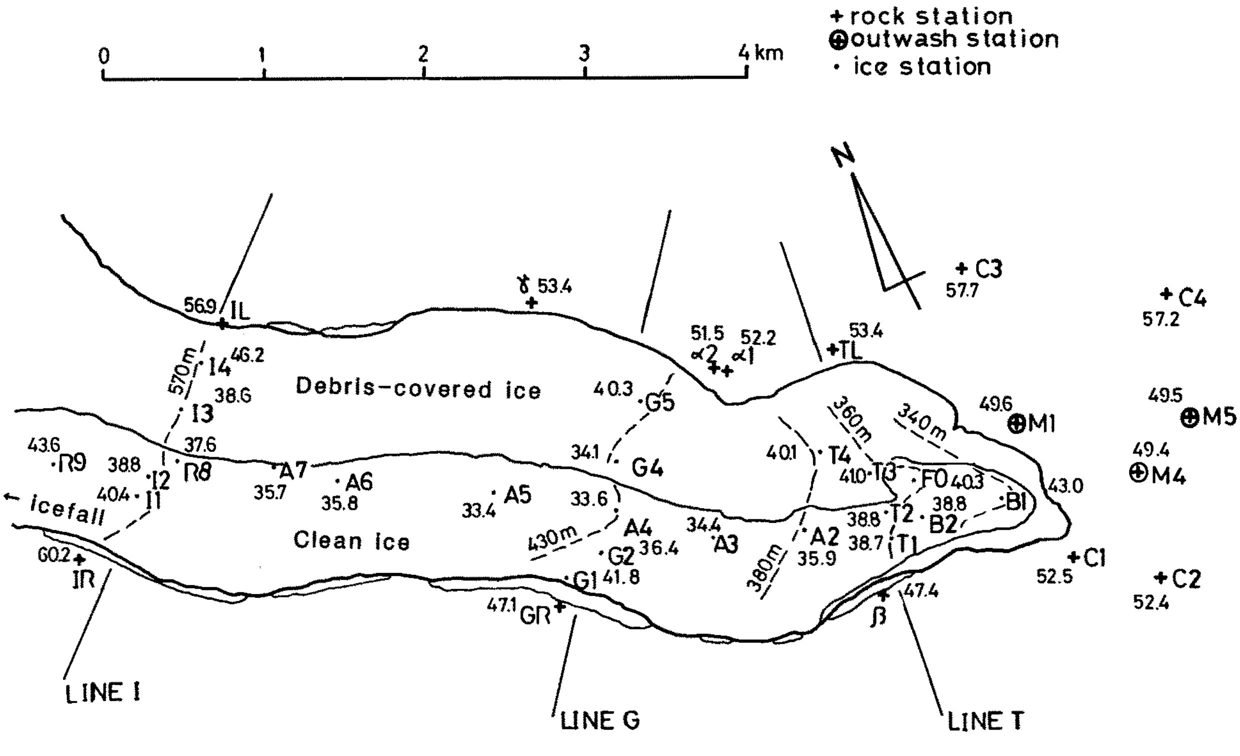

Fig. 1. Gravity stations, transverse lines and Bouguer anomalies (mgal) on Soler Glacier, ablation area.

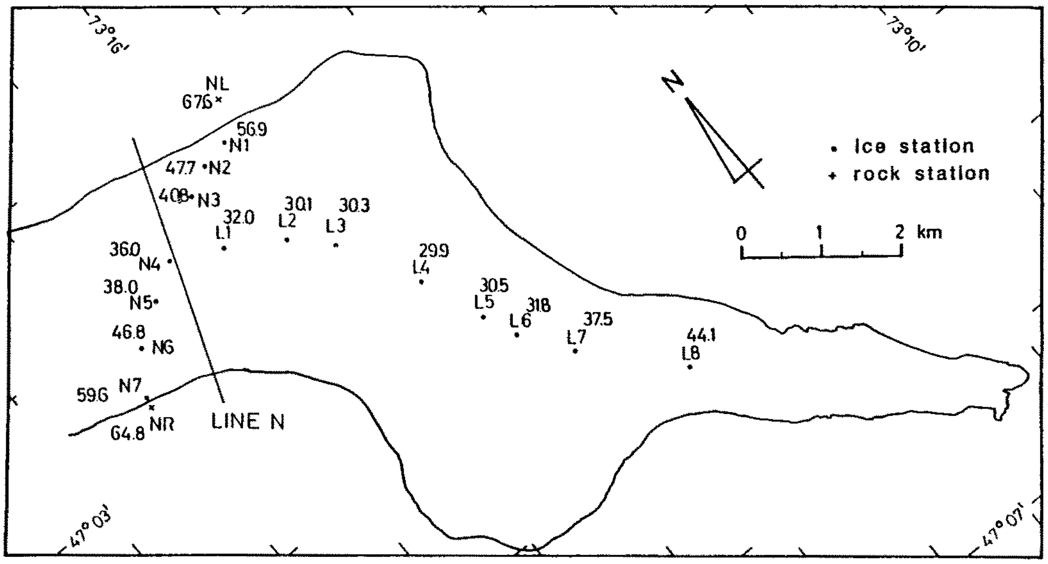

Fig. 2. Gravity stations and Bouguer anomalies (mgal) on Nef Glacier, ablation area (drawn from IGM 1 : 50,000 map).

survey traverse was closed on the way back and both the transverse and longitudinal lines linked together. The error of gravity measurement is estimated as 0.4 mgal. Elevations were measured with two Thommen 2000 altimeters, with an average error of 10 m. The horizontal position was estimated by compass bearings to neighboring peaks, with a maximum error of 250 m. In total 19 stations were measured between November 8 and 10, four of them on rock.

From November 23 to December 4 a light expedition was made into the icefield (Fig. 3 and attached Map 2, folded in). A very convenient route from Río Soler was followed, already explored in 1983/84. At that time -beginning of January, 1984- the snow line was located at an elevation of 1250 m, estimating the equilibrium line to be at 1350 m ; this time -November/December 1985- the snow line was lower, at about 1150 m. From a high camp 6 km east of the icefall of Soler Glacier, several traverse lines were made on skis during a long spell of good weather. In total, 60 stations on ice were occupied, including a 30 km long east-west line (Line J) accross the icefield to a rock point (X7) on the western edge (Map 2). Finding outcrops was in general a problem, nevertheless eight stations on rock were measured, most on nunataks. Elevation and position of stations were determined in the same way as on Nef Glacier and the maximum errors are estimated as 15 m and 500 m respectively, except for the middle stations of Line J, where positional error can increase to 1.5 km. All gravity survey traverses had at least one common station -other than the base station- and most stations were occupied twice. This way, the average observed gravity error is estimated as less than 0.5 mgal.

3. Ice divide survey

To help locate ice divides, careful altimetric readings were made, as well as observation of general topography and crevasse patterns. By means of compass bearings these divides were drawn on the IGM 1 : 50,000 map (Fig. 3). The divides were very clear between Soler and San Rafael Glaciers (following a distinctive ridge), and between Soler and León Sur Glaciers. But in the region from Soler and Nef Glaciers to San Quintín Glacier the icefield was very flat for several km, requiring careful observations to determine the divide. North of Line J an approximate ice divide between San Rafael and San Quintín Glaciers was drawn (Map 2), joining nunataks and ice ridges observed from a distance.

4. Reduction of gravity data

To compare gravity data, standard reductions were made. Gravity values (*GOBS*) are referred to

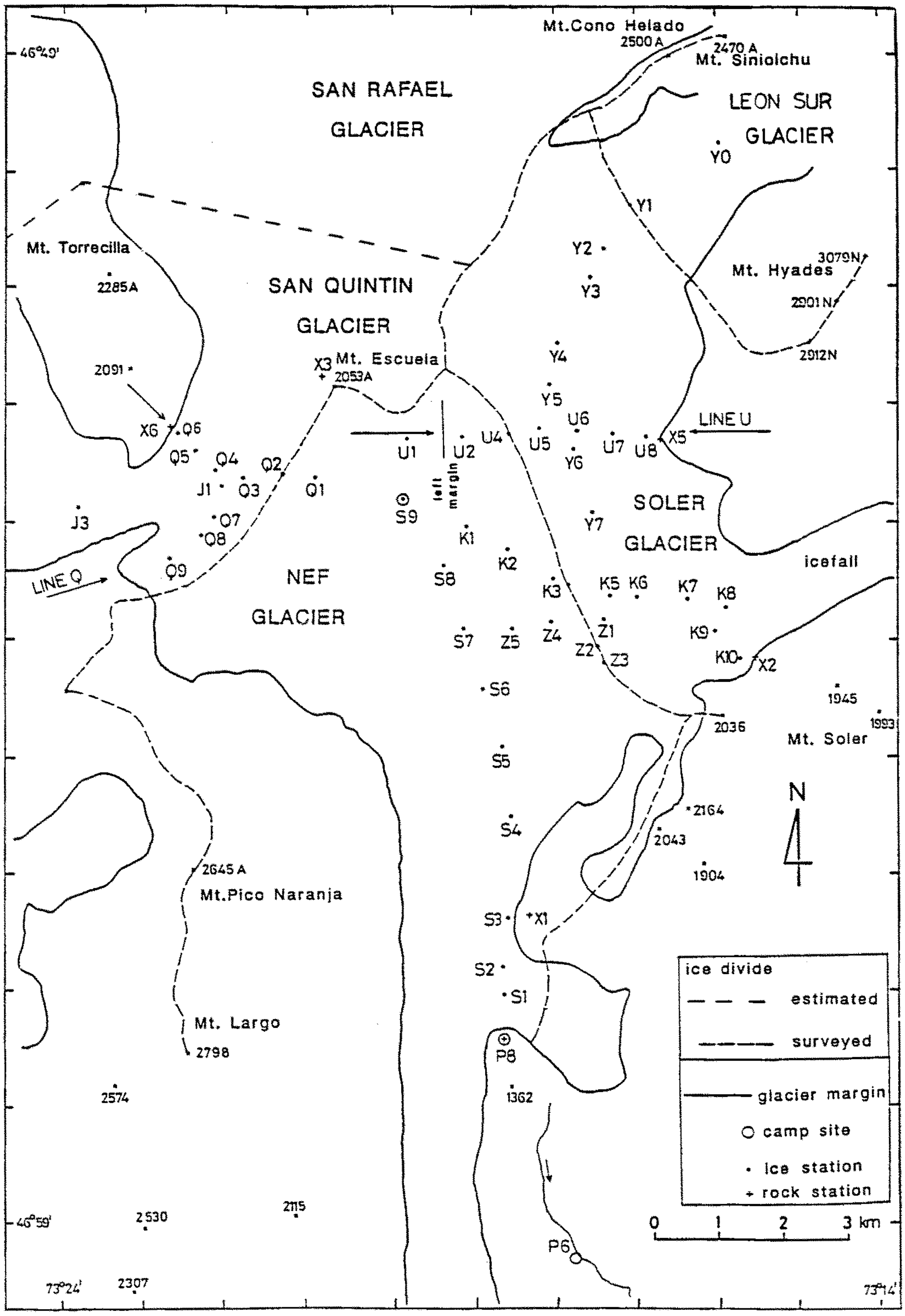

Fig. 3. Gravity stations, transverse lines and ice divides on the accumulation areas of San Quintín, Nef and Soler Glaciers (drawn from IGM 1 : 50,000 map).

an arbitrary datum of 980,770 mgal at Base Camp station M4, near the terminus of Soler Glacier.

4. 1. Bedrock and ice densities

The Patagonian Batholith, first described by Brüggen (1934), extends north and south of NPI, covering an area of 64 to 100 km wide. Even though to date no complete geological survey has been made on HPN, rocks belonging to the Patagonian Batholith have been found all around its periphery (Brüggen, 1950 ; Yoshida, 1981).

During the present gravity survey, granitic intrusive rocks were found at all rock stations, except stations IR, C3 and C4 on the ablation area of Soler Glacier, where metamorphic rocks were found. According to Yoshida (1981), these rocks belong to the Metamorphic Basement, the oldest rock unit of the region (upper Paleozoic), which was intruded by a batholith in the Cretaceous, developing a reduced aureola of contact metamorphism some hundred meters thick. A granitic rock density of 2.67 Mg/m^3 was adopted for all computations and an ice density of 0.9 Mg/m^3, the contrast being 1.77 Mg/m^3.

4. 2. Free air corrections (FC)

All gravity values were reduced to sea level, using the factor 0.3081 mgal/m, obtained by considering :

$$FC = \frac{2g_oH}{R}$$

g_o (theoretical gravity at sea level) is obtained from the Geodetic Reference System formula of 1967 (GRS 67) :

$g_o = 978{,}031.85\ (1+0.005278895 \sin^2\rho + 0.000023462 \sin^4 \rho)$

ρ : latitude of Base Camp gravity station (46°54′ 55″)

The Earth's radius (R) for Base Camp station was estimated using the values of GRS 67 for the elipsoid, which results in $R=6{,}366{,}753$ m.

Elevations (H) are based on Base Camp station M4 (277 m), determined by averaging altimetric readings from Lake Plomo (201 m on IGM 1 : 50,000 map).

4. 3. Bouguer corrections (BC)

The effect of an infinite plate of 2.67 Mg/m^3 between the station and sea level was subtracted : 0.1119 mgal/m. For Soler Glacier, where precise elevation data exist, the combined *FC* and *BC* error was 0.02 mgal (*i. e.* negligible). Instead, for Nef Glacier and the icefield, where only altimetric data exist (error of 10 to 15 m), it was large : 2 and 3 mgal respectively.

4. 4. Latitude corrections (LC)

For each station GRS 67 formula was applied, subtracting the datum value of Base Camp. This correction increases northward at a rate of 0.8 mgal/km in the area ; thus the error involved on Soler Glacier is negligible, but at Nef Glacier it is 0.2 mgal and on the icefield 0.4 mgal. On Line J, a maximum *LC* error of 1.2 mgal was obtained.

4. 5. Terrain corrections (TC)

Due to very steep valley walls at Soler Glacier, the *TC* becomes one of the least certain additions to gravity readings. On Nef Glacier and the icefield the topography near the stations was not so rough. Hammer's method (1939) was used, in which the area around the station is divided in graticules (zones and compartments), each with a known gravity effect per meter of average elevation difference with the station. Mean elevations of graticules around each station up to zone M (about 22 km from the station) were estimated from IGM 1 : 50,000 maps, which covered all of the study area. On the icefield, contour lines had to be inferred and sometimes big differences existed between altimetric readings and map elevations. Rock density (2.67 Mg/m^3) was used for all graticules. This approximation is not so good on the icefield, where most graticules lie on the glacier, but on the other hand topography is quite flat. Kanasewich (1963) and Crossley and Clarke (1970) considered both rock and ice densities for *TC*, but this procedure needs an estimation of the ice thickness. Terrain corrections ranged up to 34.4 mgal for station IR on Soler Glacier, and repeated computations of *TC* were accurate to within 1 mgal for this station. At Nef Glacier and the icefield, the *TC* error was estimated as 0.5 mgal. The gravity effect of outer zone M accounted on an average for about 10 % of the total *TC*. *TC* correction for the topography more than 22 km away should be small and very similar between nearby stations. Nevertheless, this effect can be removed as part of a regional gravity gradient term, as described below.

4. 6. Bouguer anomaly (BA)

Here we define the Bouguer anomaly as the observed gravity value minus the free air, Bouguer, latitude and terrain corrections. This anomaly indicates a combination of the following four effects : 1) large scale regional gravity gradient due to variations in crustal structure, 2) local density variations of underlying material, 3) terrain effects of areas more distant than zone M, and 4) mass deficiency effect of the glacier. The purpose of the gravity method is to eliminate the first three effects (grouped together in a regional gravity gradient term *RG*) and estimate ice thicknesses from net, or residual anomalies (*RA*).

Thus, $RA = BA - RG$

In the field it was not possible to measure gravity far enough from the glacier so as to neglect the effect of the glacier's mass deficiency, thus none of the stations was free from this effect. The regional gravity on rock points, unbiased with respect to ice, had to be either calculated on transverse profiles, or estimated roughly at other stations.

Considering the combined effect of observed gravity and the corrections, the maximum *BA* error was estimated as 1.3 mgal for Soler Glacier, 3.1 mgal for Nef Glacier, 4.4 mgal for the icefield and 5.2 mgal for Line J. In Fig. 1 and Table 1 the *BA* values of Soler Glacier are presented.

Table 1. Gravity values, Soler Glacier, ablation area.

DIST.	distance along the traverse line	BA	Bouguer anomaly
H	elevation	RG	regional gradient
GOBS	observed gravity	RA	residual anomaly
LC	latitude correction	BED	bedrock elevation
TC	terrain correction	T	ice thickness
FC	free air correction	GF	gravity factor
BC	Bouguer correction		

RA values were rounded off to a two-digit significant number, because the error is greater than 1 mgal (see text 6.).
The values of BED, T and GF were not rounded off, the error being indicated in the text (6.) and Table 4.

ST.	DIST. m	H m	GOBS mgal	LC mgal	TC mgal	FC mgal	BC mgal	BA mgal	RG mgal	RA mgal	BED m	T m	GF m/mgal
LINE I													
IL	0	553.6	−57.6	−19.6	25.5	170.6	−62.0	56.9	62.4	−6			
I4	250	571.3	−66.8	−19.7	20.7	176.0	−03.9	46.2	63.3	−17	456	115	8.7
I3	560	569.8	−71.2	−19.9	17.9	175.6	−63.8	38.6	64.3	−26	−5	575	23.6
R8	890	565.2	−71.8	−20.1	18.6	174.1	−63.3	37.6	64.6	−27	145	420	16.6
I2	1020	573.4	−73.4	−20.1	19.8	176.7	−64.2	38.8	65.7	−27	109	464	18.6
I1	1160	577.2	−73.4	−19.9	20.5	177.8	−04.6	40.4	66.3	−26	22	555	22.9
IR	1630	621.0	−75.9	−20.1	34.4	191.3	−79.5	60.2	69.1	−9			
LINE G													
G5	0	434.2	−35.3	−20.9	11.4	133.8	−48.6	40.3	52.6	−12	261	173	14.1
G4	470	429.5	−42.1	−21.1	13.1	132.3	−48.1	34.1	51.1	−17	99	331	19.5
A4	690	432.2	−44.1	−21.3	14.2	133.2	−48.4	33.6	50.1	−17	197	235	14.2
G2	960	410.6	−39.2	−21.5	16.5	126.5	−46.0	36.4	49.5	−13	158	253	19.3
G1	1160	407.3	−36.8	−21.5	20.2	125.5	−45.6	41.8	49.7	−8	345	62	7.8
GR	1360	414.7	−36.2	−21.6	23.6	127.8	−46.4	47.1	49.4	−2			
LINE T													
TL	0	384.4	−16.0	−21.0	15.0	118.4	−43.0	35.4	54.5	−1			
T4	640	376.8	−25.2	−21.5	12.9	116.1	−42.2	40.1	51.6	−12	164	213	18.5
T3	820	362.2	−22.4	−21.0	13.3	111.6	−40.5	41.0	51.4	−10	271	101	9.7
T2	1050	364.4	−24.8	−21.0	13.1	112.3	−40.8	38.8	51.1	−12	183	181	14.7
T1	1220	351.8	−22.0	−22.1	13.8	108.4	−39.4	38.7	51.0	−12	60	292	23.7
BETA	1560	381.9	−21.4	−22.3	16.1	117.7	−42.7	47.4	50.8	−3			

Table 1. (continued)

ST.	H	GOBS	LC	TC	FC	BC	BA	RG	RA	BED	T	GF
Stations not belonging to transverse lines												
R9	614.0	−79.3	−19.9	22.4	189.2	−68.7	43.6	64.3	−21	156	458	20.0
A7	534.5	−65.5	−20.4	16.7	164.7	−59.8	35.7	60.4	−25	115	420	17.0
A6	513.8	−61.1	−20.5	16.6	158.3	−57.5	35.8	57.7	−22	142	372	17.0
A5	458.8	−50.6	−21.0	15.0	141.4	−51.4	33.4	52.6	−19	152	307	16.0
A3	396.1	−35.4	−21.7	13.7	122.0	−44.3	34.4	49.2	−15	189	207	14.0
A2	377.7	−29.5	−21.8	13.1	116.4	−42.3	35.9	49.7	−14	178	200	14.5
F0	363.3	−22.6	−21.8	13.5	111.9	−40.7	40.3	51.7	−11	226	137	12.0
B2	355.6	−22.2	−22.0	13.3	109.6	−39.8	38.8	51.5	−13	102	254	20.0
B1	343.8	−17.2	−22.1	14.9	105.9	−38.5	43.0	51.3	−8	236	108	13.0

5. Interpretation of the anomalies

Supposing we obtain residual anomalies (*RA*), the problem is then to estimate an ice body shape and calculate its gravity effect to fit such anomalies. The easiest approach is converting linearly the anomalies into depths by using the factor for an infinite slab of ice (about 13 m/mgal). For ice caps with smooth subglacial topography such as Anvers Island, Antarctic Peninsula, this is a good approximation (Casassa, 1984), but in valley glaciers this premise tends to make glacier depths too shallow, because it does not account for bedrock rise toward the margins. As pointed out by Corbatō (1965), subsequent boreholes have confirmed this, as well as comparison of ice thicknesses calculated by more precise analytical methods (namely Talwani's method, 1959) and the infinite slab formula, (*e.g.* Moribayashi, 1978). Bentley (1964), by comparing seismic ice thicknesses with gravity anomalies in Antarctica, found a larger empirical factor of 20 m/mgal, valid for ice sheet areas with rough glacier bed topography.

Precise analytical methods have been developed by Talwani *et al.* (1959) and Talwani and Ewing (1960), to estimate the gravity anomaly of two dimensional and three dimensional irregular bodies, respectively. In the present study, a two dimensional (x, z) approach was adopted because of lack of complete gravity coverage on glaciers and simple glacier shapes involved in general. Z is the vertical coordinate and x the horizontal. The glacier's cross section lies within the (x, z) plane and is polygonized. The third dimension was supposed to be infinite along an axis perpendicular to the cross section, parallel to the direction of the flow. The anomalies produced by the body at any station can be computed based on the coordinates of the cross section points. By successive iterations a best fit is found between *RA* and the anomalies calculated by Talwani's method. In programming the method, a corrected and more suitable formula (Tsutsui, 1981) was used. The input of the method is the polygonized cross section of the glacier, while the output is the calculated Talwani's anomaly (*TA*). *TA* values are then compared to *RA* and the difference (*DELTA*) multiplied by a factor between 10 and 30 to form a new cross section, which in turn constitutes the new input to the program. For the first iteration, an initial cross section had to be assumed. Convergence was quite fast, needing in general twenty iterations before attaining a final cross section with an average *DELTA* of less than 0.1 mgal.

6. Bedrock topography

6. 1. Soler Glacier

From Fig. 1 it is seen that Soler Glacier is a simple shaped glacier tongue of about 1.5 km wide and 7 km long. Talwani's method was applied at three transverse lines (Lines I, G and T). At first two dimensional parabolas with vertical symmetry axis were fitted to the Bouguer anomalies (Corbatō, 1964), thus obtaining a first approximation of both ice depths and gravity effect of the glacier at its edges. This way, the regional gradient (*RG*) was estimated by least square fitting of a third degree polynomial, and residual anomalies (*RA*) were found. By subsequently applying Talwani's method and recalculating *RG*, a good fit was found with a *DELTA* mean square error of less than 0.1 mgal. In Fig. 4 the final cross section and gravity anomalies are shown (*RA* and *TA*). On

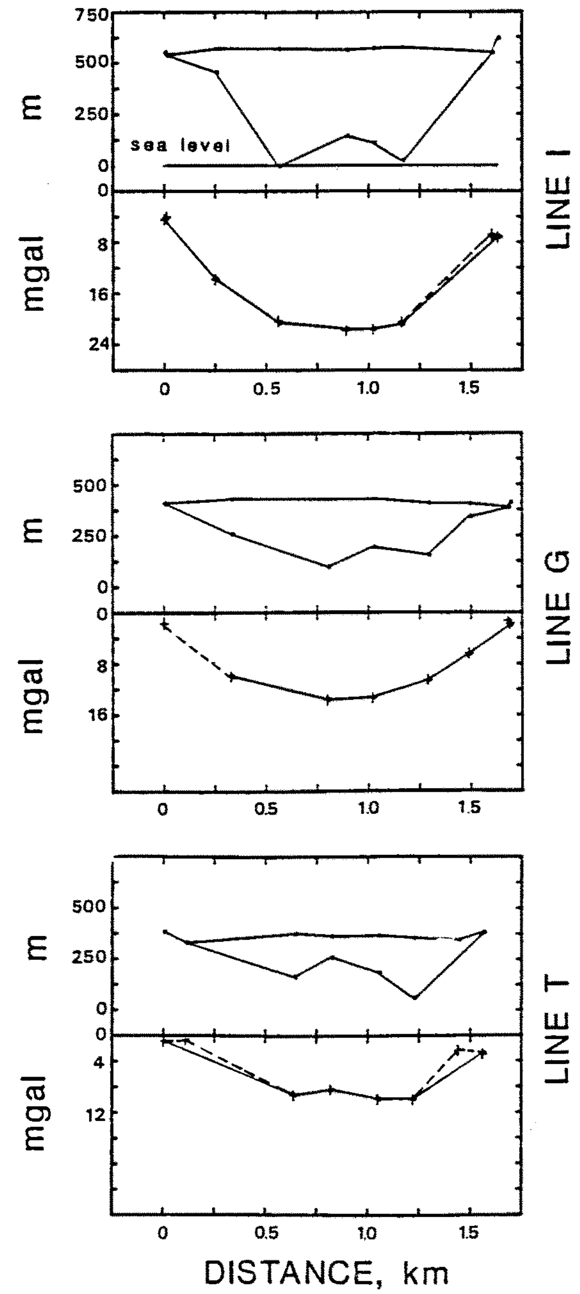

Fig. 4. Transverse profiles of depth (m) and gravity anomaly (mgal) along three lines on Soler Glacier, ablation area. In the lower half of the figures both the obtained residual anomalies (*RA*) and the calculated Talwani's anomalies (*TA*) are plotted with a continuous and dotted line respectively. These two curves overlap, indicating a good fit.

the three cross sections two distinctive subglacial troughs appear close to the margins, presumably corresponding to drainage sections from the two sources which feed Soler Glacier : Mount Hyades on the left and the icefield on the right. Aniya and Naruse (1985) estimated maximum ice thicknesses from valley walls extrapolations at Soler's upper (Line I) and middle (Line G) sections to be 290 and 240 m, smaller than our values of 575 and 330 m respectively. In the text, rounded values of ice thickness are presented, whereas originally calculated values are shown in Tables 1, 2 and 3. Estimated errors are presented in Table 4.

To estimate ice thickness at stations outside traverse lines, a gravity factor (*GF*) from Talwani's thicknesses (*T*) was calculated, as *T*/*RA* (m/mgal) and extrapolated to neighboring stations (Table 1). Such factors ranged from 7.8 m/mgal to 23.6 m/mgal, with an average of 16.5 m/mgal, a value between the infinite slab ice factor and Bentley's (1964) value. This way a longitudinal profile of the glacier was drawn (Fig. 5).

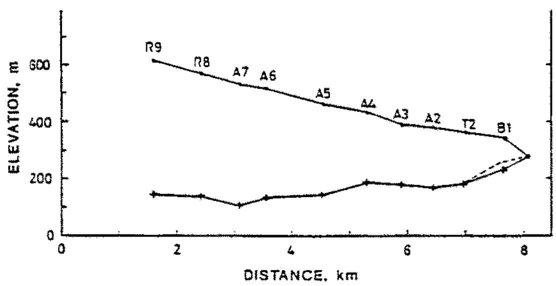

Fig. 5. Longitudinal depth profile on Soler Glacier, ablation area. The dotted line indicates ice thickness corrected by the gravity effect of underlying outwash material.

6. 1. 1. *Outwash material*

A large rise of the bedrock can be observed downstream from station A2, probably due to underlying outwash material. By comparing Bouguer anomalies between M1, M4, M5 and neighboring rock stations on the valley margins, a gravity deficiency of 4.3 mgal is observed. We will suppose that this gravity contrast is due to the effect of less dense outwash material which fills the valley downstream from Soler Glacier. An average rock density of 2.75 Mg/m^3 was adopted, because of the presence of denser metamorphic rocks on the left bank of the valley. Estimating a density of 2.0 Mg/m^3 for the outwash material, a density contrast of 0.75 Mg/m^3 results. By using the infinite slab formula, an outwash thickness of 140 m was estimated for the area near the

Table 2. Gravity values, Nef Glacier, ablation area. For column headings and explanations, see Table 1.

ST.	DIST. m	H m	GOBS mgal	LC mgal	TC mgal	FC mgal	BC mgal	BA mgal	RG mgal	RA mgal	BED m	T m	GF m/mgal
LINE N													
NL	0	849	−75.9	−31.9	8.8	261.6	−95.0	67.6	73.8	−6			
N1	500	688	−51.1	−32.3	5.3	212.0	−77.0	56.9	74.0	−17	627	61	3.6
N2	675	712	−64.6	−32.4	5.0	219.4	−79.7	47.7	74.0	−26	192	520	19.8
N3	950	733	−74.6	−32.5	4.2	225.8	−82.0	40.8	74.1	−33	67	666	20.0
N4	1600	765	−85.9	−32.9	4.7	235.7	−85.6	36.0	74.4	−38	234	531	13.8
N5	2000	761	−82.9	−33.1	4.7	234.5	−85.2	38.0	74.5	−37	−245	1006	27.6
N6	2450	793	−80.4	−33.4	5.0	244.3	−88.8	46.8	74.7	−28	614	179	6.4
N7	3075	772	−65.6	−33.8	7.6	237.9	−86.4	59.6	74.9	−15	480	292	19.1
NR	3130	767	−60.7	−33.9	8.9	236.3	−85.9	64.8	74.9	−10			
LINE L													
N4	0	765	−85.9	−32.9	4.7	235.7	−85.6	36.0	74.4	−38	234	531	13.8
L1	700	740	−83.8	−33.1	3.7	228.0	−82.8	32.0	74.4	−42	146	594	14.0
L2	1500	712	−79.3	−33.5	3.2	219.4	−79.7	30.1	74.4	−44	92	620	14.0
L3	2100	699	−76.2	−33.8	3.2	215.4	−78.2	30.3	74.4	−44	82	617	14.0
L4	3250	682	−72.4	−34.7	3.2	210.1	−76.3	29.9	74.4	−45	59	623	14.0
L5	4150	648	−65.0	−35.3	3.7	199.6	−72.5	30.5	74.4	−44	33	615	14.0
L6	4625	627	−59.5	−35.7	4.0	193.2	−70.2	31.8	74.4	−43	31	596	14.0
L7	5375	586	−46.6	−36.2	5.3	180.5	−65.6	37.5	74.4	−37	69	517	14.0
L8	6825	537	−31.3	−37.1	7.2	165.5	−60.1	44.1	74.4	−30	113	424	14.0

Table 3. Gravity values, icefield. For column headings and explanations, see Table 1.

ST.	DIST. m	H m	GOBS mgal	LC mgal	TC mgal	FC mgal	BC mgal	BA mgal	RG mgal	RA mgal	BED m	T m	GF m/mgal
LINE U													
X5	0	1792	−269.1	−18.4	14.1	552.1	−200.6	78.2	81.7	−4			
U8	230	1779	−269.2	−18.3	9.6	548.1	−199.1	71.2	81.5	−10	1621	158	15.3
U7	780	1795	−276.4	−18.2	5.5	553.0	−200.9	63.0	81.0	−18	1566	229	12.7
U6	1305	1823	−289.0	−18.2	4.2	561.7	−204.0	54.6	80.5	−26	1469	354	13.7
U5	1905	1825	−294.7	−18.2	3.4	562.3	−204.3	48.6	79.9	−31	1263	562	18.0
U4	2355	1828	−294.6	−18.2	3.1	563.2	−204.6	48.9	79.5	−31	1229	599	19.6
U2	3105	1832	−281.1	−18.3	3.1	564.4	−205.1	63.1	78.8	−16	1686	146	9.3
LINE Q													
Q8	0	1683	−280.1	−19.5	2.0	518.5	−188.4	32.5	64.1	−32	1248	435	13.8
Q7	400	1677	−284.0	−19.3	1.9	516.7	−187.7	27.6	64.1	−37	839	838	23.0
J1	900	1681	−284.7	−18.9	2.0	517.9	−188.2	28.2	64.1	−36	1090	591	16.5
Q4	1150	1671	−279.7	−18.7	2.0	514.8	−187.0	31.3	64.1	−33	1015	656	20.0
Q5	1600	1683	−273.6	−18.5	2.3	518.5	−188.4	40.4	64.1	−24	1489	194	8.2
Q6	2000	1708	−273.1	−18.3	2.9	526.2	−191.2	46.6	64.1	−18	1420	288	16.5
X6	2150	1709	−269.5	−18.2	3.5	526.5	−191.3	51.1	64.1	−13			
LINE J													
X6	0	1709	−269.5	−18.2	3.5	526.5	−191.3	51.1	64.1	−13			
J4	2950	1511	−261.9	−18.9	1.2	465.5	−169.1	16.8	68.9	−52	797	714	13.7
J5	5250	1441	−261.3	−18.8	0.9	444.0	−161.3	3.5	72.7	−69	366	1075	15.5
J6	8350	1371	−241.1	−19.3	0.7	422.4	−153.5	9.2	77.8	−69	438	933	12.6
J7	10200	1339	−230.7	−19.1	0.8	412.5	−149.9	13.7	80.8	−67	379	960	14.3
J8	11950	1303	−217.4	−18.8	0.9	401.5	−145.8	20.2	83.7	−64	596	707	11.1
J9	13850	1249	−214.3	−19.1	0.7	384.8	−139.8	12.3	86.8	−75	211	1038	13.9
J10	15750	1235	−218.7	−18.8	0.6	380.5	−138.2	5.4	89.9	−85	−223	1458	17.3
J11	17950	1225	−205.1	−17.6	0.8	377.4	−137.1	18.4	93.5	−75	212	1013	13.5
J12	21350	1117	−161.2	−17.6	0.9	344.1	−125.0	41.2	99.0	−58	497	620	10.7
J13	22950	1115	−168.4	−18.1	1.3	343.5	−124.8	33.6	101.7	−68	−201	1316	19.3
J14	24800	1111	−141.6	−18.5	2.7	342.3	−124.4	60.5	104.7	−44	424	687	15.5
X7	25300	1182	−134.9	−18.5	7.0	364.2	−132.3	85.5	105.5	−20			

Table 3. (continued)

ST.	H	GOBS	LC	TC	FC	BC	BA	RG	RA	BED	T	GF
Stations not belonging to transverse lines												
Q1	1729	−288.1	−18.9	1.7	532.7	−193.5	33.9	75.8	−42	1100	629	15.0
Q2	1728	−293.2	−18.8	1.8	532.4	−193.4	28.7	73.5	−45	1013	715	16.0
Q3	1705	−291.3	−18.9	1.8	525.3	−190.8	26.1	68.0	−42	993	712	17.0
S1	1359	−187.0	−25.5	4.8	418.7	−152.1	58.9	69.7	−11	1197	162	15.0
S2	1373	−194.3	−25.0	4.7	423.0	−153.7	54.7	70.1	−15	1142	231	15.0
S3	1494	−214.7	−24.5	4.9	460.3	−167.2	58.8	70.8	−12	1314	180	15.0
S4	1579	−239.6	−23.1	3.6	486.5	−176.7	50.6	68.8	−18	1306	273	15.0
S5	1598	−251.4	−22.3	2.9	492.3	−178.9	42.7	69.8	−27	1191	407	15.0
S6	1617	−257.0	−21.5	2.6	498.2	−181.0	41.3	71.4	−30	1165	452	15.0
S7	1656	−270.3	−20.4	2.3	510.2	−185.4	36.4	73.4	−37	1100	556	15.0
S8	1684	−274.8	−19.9	2.1	518.8	−188.5	37.7	75.7	−38	1115	569	15.0
S9	1725	−276.4	−19.1	1.8	531.5	−193.1	44.8	77.2	−32	1238	487	15.0
Z1	1705	−273.7	−20.6	4.1	525.3	−190.8	44.3	75.8	−32	1232	473	15.0
Z2	1709	−273.0	−21.0	4.1	526.5	−191.3	45.4	74.8	−29	1269	440	15.0
Z3	1721	−268.0	−21.2	5.0	530.2	−192.6	53.4	74.1	−21	1411	310	15.0
Z4	1696	−272.4	−20.7	2.9	522.5	−189.8	42.6	75.0	−32	1209	487	15.0
Z5	1688	−271.5	−20.8	2.5	520.1	−188.9	41.4	74.2	−33	1196	492	15.0
K1	1697	−267.2	−19.5	2.2	522.8	−189.9	48.5	77.3	−29	1264	433	15.0
K2	1700	−271.7	−19.8	2.3	523.8	−190.3	44.4	77.1	−33	1208	492	15.0
K3	1702	−276.6	−20.1	2.8	524.4	−190.5	40.0	76.6	−37	1152	550	15.0
K4	1710	−277.6	−20.1	3.0	526.9	−191.4	40.8	76.7	−36	1170	540	15.0
K5	1706	−275.2	−20.3	3.9	525.6	−191.0	43.1	76.8	−34	1200	506	15.0
K6	1673	−264.6	−20.4	4.2	515.5	−187.3	47.4	77.1	−30	1227	446	15.0
K7	1630	−253.4	−20.4	5.2	502.2	−182.4	51.2	77.8	−27	1231	399	15.0
K8	1584	−240.6	−20.4	7.0	488.0	−177.3	56.6	78.1	−22	1261	323	15.0
K9	1596	−241.3	−20.7	7.0	491.7	−178.6	58.1	77.0	−19	1312	284	15.0
K10	1602	−231.6	−21.1	9.1	493.6	−179.3	70.7	76.4	−6	1516	86	15.0
J2	1617	−269.7	−19.1	2.1	498.2	−181.0	30.6	64.1	−34	1047	570	17.0
J3	1578	−266.5	−19.1	2.1	486.2	−176.6	26.0	66.6	−41	969	609	15.0
Y0	2055	−335.3	−14.5	8.9	633.1	−230.0	62.2	82.5	−20	1750	305	15.0
Y1	2078	−339.7	−15.3	5.9	640.2	−232.6	58.6	81.3	−23	1737	341	15.0
Y2	2030	−322.5	−15.9	5.8	625.4	−227.2	65.7	81.0	−15	1800	230	15.0
Y3	1965	−310.2	−16.2	5.7	605.4	−219.9	64.8	81.0	−16	1720	245	15.0
Y4	1941	−310.9	−17.1	4.7	598.0	−217.3	57.5	80.3	−23	1599	342	15.0
Y5	1869	−299.5	−17.7	3.4	575.8	−209.2	52.8	80.2	−27	1458	411	15.0
Y6	1807	−289.5	−18.4	3.8	556.7	−202.3	50.4	80.3	−30	1388	419	14.0
Y7	1756	−276.5	−19.3	3.4	541.0	−196.5	52.0	79.4	−27	1346	410	15.0
U1	1764	−273.3	−18.3	5.0	543.5	−197.4	59.4	78.0	−19	1559	205	11.0

Table 4. Ice thickness error.

AREA	GRAVITY SURVEY TRAVERSE LINES	ESTIMATED ERROR (%)
Soler Glacier	I, G, T	15
Soler Glacier	other stations	25
Nef Glacier	N	25
Nef Glacier	L	35
icefield	U	27
icefield	Q	30
icefield	J	35
icefield	other stations	40

glacier front. Over the glacier, the gravity effect of this underlying outwash material should be subtracted from the residual anomalies (*RA*). If we consider the bedrock underlying the outwash material to have an upstream constant slope and intersect this line with the longitudinal bedrock profile of the glacier, we can estimate roughly the outwash thickness under the glacier as being 70 m for station B1 and negligible near line T. Thus, the gravity effect of outwash material is only considered important at station B1, estimating it as 2.2 mgal using the infinite slab formula. The corrected residual anomaly at B1 becomes 6 mgal, equivalent to 80 m of ice (see Fig. 5).

6. 2. Nef Glacier

As seen from Fig. 2, Nef Glacier in its middle section bends sharply to the south, narrowing toward the snout. Due to lack of stations, a three dimensional calculation could not be made, so a transverse Line N was drawn perpendicular to the glacier margins and Talwani's two dimensional method was applied. Regional gradient (*RG*) was subtracted linearly on ice stations between both glacier margins (rock stations NL and NR), by calculating the ice gravity effect at both these stations in subsequent iterations.

A very large ice thickness (T) of 1000 m resulted at cross section point N5, representing a deep subglacial trough. On both margins less pronounced troughs can be observed. For longitudinal Line L ice thicknesses were computed from residual anomalies by using a gravity factor of 14 m/mgal, similar to Talwani's factor obtained at the middle station of Line N (N4). Results are presented in Table 2 and Figs. 6 and 7.

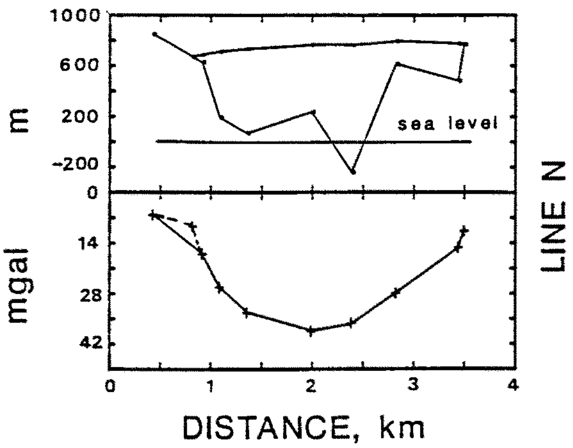

Fig. 6. Transverse profile of depth (m) and gravity anomaly (mgal) along line N, ablation area of Nef Glacier. *RA* is plotted with continuous line and *TA* with dotted line ; both curves overlap except on the left margin.

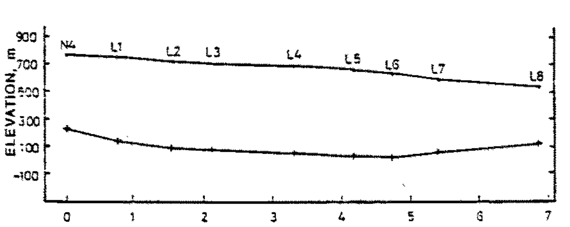

Fig. 7. Longitudinal depth profile on Nef Glacier, ablation area.

6. 3. Icefield

Talwani's method was applied at transverse Lines U on Soler Glacier and Q on San Quintín Glacier (Fig. 3), and east-west transverse Line J on the icefield (Map 2). Even though on Line U no right margin existed, the right margin was set at a point 400 m east of U2, over a steep ice slope where the ice thickness was supposed to be small. For this cross section a two dimensional approach is quite accurate. Not so for Line Q where the glacier narrows remarkably flowing to the west through a gap between nunataks (Mt. Torrecilla and Mt. Largo). Here, the left margin was set on ice covered slopes, including unsurveyed station Q9 in the profile. The final profile was calculated in the same way as before. The glacier effect on rock stations outside these profiles was estimated using a formula for a half thin infinite slab (Dobrin, 1976). A third degree least square polynomial was fitted to the regional values off the glacier, large errors being expected due to few rock data and unprecise glacier effect estimation. Results are presented in Fig. 8 and Table 3. On Line U a very smooth profile resulted, with a maximum ice thickness of 600 m at station U4 below the ice divide. On Line Q a rough bedrock profile resulted, with a maximum of 840 m on station Q7.

Finally, on transverse Line J an east-west profile was chosen, joining rock station X6 to J4 and all the stations west of J4 to rock point X7. This cross section is supposed to extend infinitely toward the north and south : a good approximation for the center of the traverse line but not so good near the edges. The regional gradient between X6 and X7 was supposed to be linear. From residual anomalies, a regional gradient of +1.6 mgal/km going away from the mountain range results, similar to the value of +1.5 mgal/km for isostatically adjusted mountains like the Alps (Marangunić, 1972). As seen in Fig. 8, the western part of the profile showed rough subglacial topography, partly below sea level. There are two clear subglacial troughs, the bigger one having a large value of 1460 m of ice thickness. Contrastingly, on the eastern part, bedrock topography is smooth and rises constantly to the east. The mean gravity factor (*GF*) value obtained for Talwani's transverse profiles on the icefield was 15 m/mgal (see Table 3), smaller than Bentley's empirical factor for Antarctica but larger than the infinite plate factor.

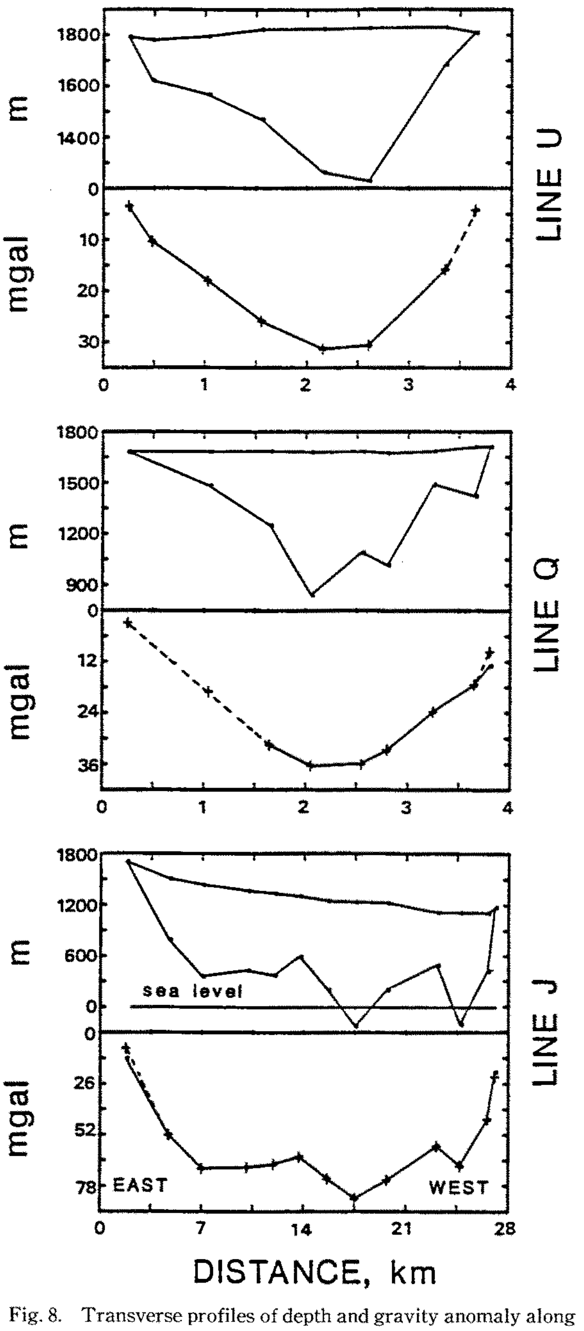

Fig. 8. Transverse profiles of depth and gravity anomaly along three lines on the icefield. *RA* is plotted with continuous line and *TA* with dotted line. Both *RA* and *TA* curves overlap, except on the glacier margins. On line Q only one gravity measurement was made on the left half of the glacier (station Q8).

To estimate ice thicknesses on the rest of the icefield stations, the mean *GF* of 15 mgal/m was used, as shown in Table 3, except for few stations near to transverse profiles. Thus, a complete west-east profile joining the icefield with Soler Glacier-ablation area, was made (Fig. 9). The bed profile is quite flat east of the ice divide between San Quintín and Nef glaciers, and reaches a threshold elevation of 1260 m at stations K2 and K8 close to the icefall of Soler Glacier. Finally, in Fig. 10 a longitudinal profile of Soler Glacier is shown, from the ice divide with León Sur Glacier to the snout.

7. Accuracy of the results

Regional gravity gradient errors were estimated to be 0.3, 0.6 and 1.0 mgal for Soler Glacier, Nef Glacier and the icefield, respectively. Considering the Bouguer anomaly error already described in 3.6., we obtain the following errors in the residual anomaly (*RA*) : 1.6 mgal for Soler Glacier, 3.7 mgal for Nef Glacier, 5.4 mgal for the icefield and 6.2 mgal for Line J. These errors represent maximum expected *RA* errors between stations. To estimate the ice thickness error, different sets of *RA* values within the error described were input in every transverse line to Talwani's program and by iteration a new ice thickness was obtained. The maximum difference between this new ice thickness and the original ice thickness obtained for each line was considered to be the error. By averaging this error along each line, a maximum ice thickness error expressed in % was obtained. For stations not belonging to transverse lines a 10 % error was added, due to gravity factor indetermination. These errors (shown in Table 4) represent an estimation of the maximum ice thickness errors to be expected.

8. Concluding remarks

The gravity survey was found to give a good preliminary estimation of ice thicknesses, specially by using Talwani's (1959) method. Talwani's two dimensional method was applied to 7 transverse lines on Soler Glacier, Nef Glacier and the icefield. For stations not belonging to these transverse lines, ice thickness was estimated by applying a gravity factor to the residual anomalies.

On Soler glacier, two subglacial troughs with a maximum ice thickness of 575 ± 85 m were found on three cross sections along the glacier and are inter-

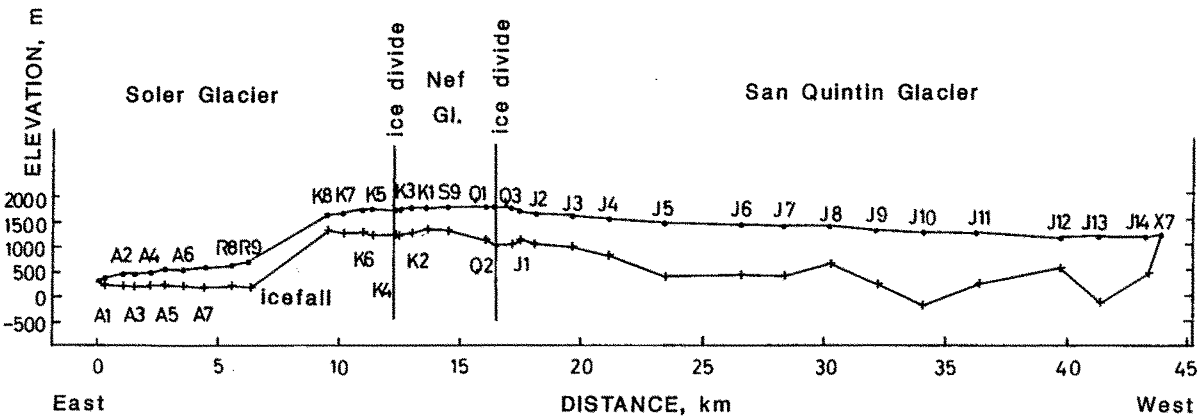

Fig. 9. East-west transverse depth profile of the Northern Patagonia Icefield.

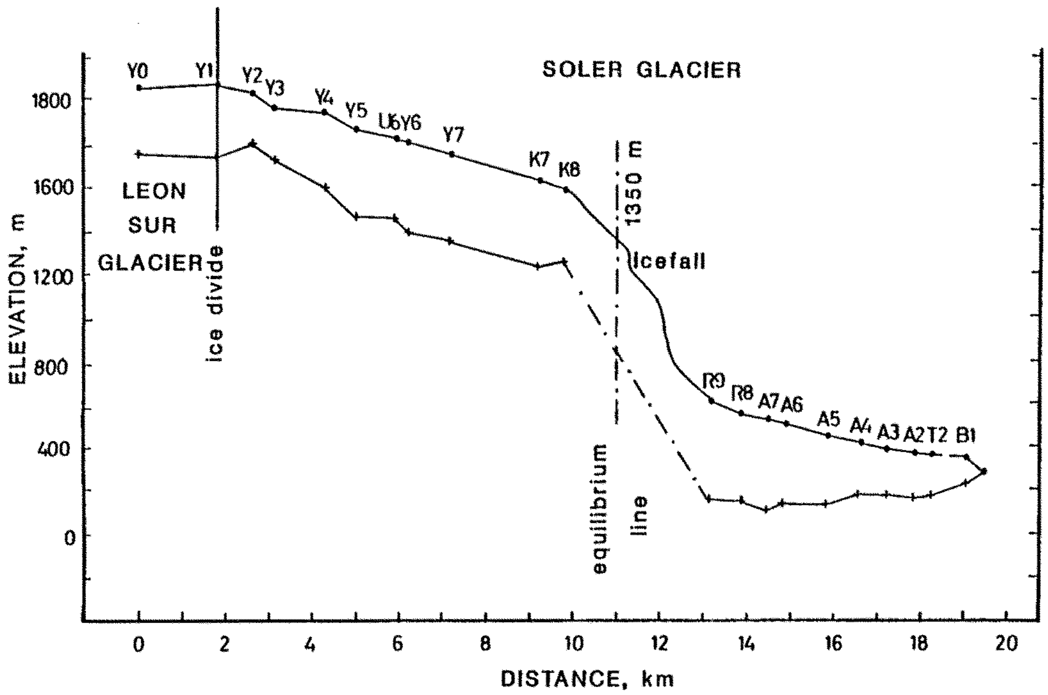

Fig. 10. Longitudinal depth profile of Soler Glacier (accumulation and ablation areas).

preted to correspond to drainage sections from the two ice sources of the glacier. On Nef Glacier a deep subglacial trough having an ice thickness of 1000 ± 250 m was found. On the icefield, general bedrock profile on an east-west line was very rough on the west, sometimes extending below sea level with a maximum thickness of 1460 ± 500 m. The bedrock rises smoothly to the east, where the ice divides are located, up to a threshold elevation of 1260 m over the Soler Glacier icefall, with an ice thickness of 320 ± 130 m. As pointed out by Aniya and Naruse (1985), this threshold elevation largely controls the ice spilling to outlet glaciers.

In the future, it would be very interesting to continue more detailed ice thickness measurements over a larger area of the icefield. The gravity method proved very adequate for the field conditions of Patagonia, even though limitations are recognized on its accuracy, specially if precise elevation data are not available. The large extent of the icefield in nunatak-free areas should permit the use of more precise radio echo soundings, even though multiple echos due to englacial water and rough subglacial topography are to be expected.

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Resumen

Espesor de hielo deducido a partir de anomalías gravimétricas en los Glaciares Soler y Nef y el campo de hielo, Hielo Patagónico Norte (HPN)

Desde Octubre a Diciembre de 1985 se realizó mediciones gravimétricas en el área de ablación de los glaciares Soler y Nef y el campo de hielo, HPN. En el Glaciar Soler se midió en tres líneas transversales en la sección alta, media y baja : Líneas I, G y T respectivamente y en nueve otras estacioned (Fig. 1). Aquí existen datos precisos por triangulación de cotas y posiciones de estaciones. En el Glaciar Nef se midió en una línea transversal N y en una línea longitudinal L (Fig. 2). Posteriormente se realizó una expedición liviana al campo de hielo, realizando observaciones gravimétricas en tres líneas transversales en la zona de acumulación : Línea U en los Glaciares Soler y Nef ; y Líneas Q y J en el Glaciar San Quintín (Fig. 3). La Línea J formó parte de una travesía este-oeste de 30 km que cubrió hasta el borde rocoso de la lengua del Glaciar San Quintín (ver Mapa 2 anexo). Además se midió en otras 23 estaciones en el campo de hielo. Tanto en el Glaciar Nef como en el campo de hielo el estudio gravimétrico tiene un carácter preliminar, dado que las cotas son altimétricas.

Se obtuvo las anomalías de Bouguer a partir de la gravedad observada, sometida a las correcciones de aire libre, Bouguer, topografía y latitud. Las anomalías residuales debidas solamente al hielo se obtuvieron substrayendo el gradiente regional estimado de las anomalías de Bouguer (Tablas 1, 2 y 3). Se aplicó el método bidimensional de Talwani (1959) a los siete perfiles transversales, resultando valores máximos de espesor de hielo de 575 $\pm$ 85 m en el Glaciar Soler (Línea I, Fig. 4), 1000 $\pm$ 250 m en el Glaciar Nef (Línea N, Fig. 6) y 1460 $\pm$ 500 m en el sector occidental del campo de hielo (Línea J, Fig. 8). Para las estaciones no pertenecientes a los perfiles transversales se calculó un espesor de hielo extrapolando los factores de gravedad obtenidos por el método de Talwani. En la Tabla 4 se muestra una estimación de los errores de espesor de hielo involucrados.