INVESTIGATIONS OF KING GEORGE ISLAND ICE COVER USING ERS-1/SAR AND SPOT IMAGERY

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Abstract

This paper presents preliminary results of a study based on the analysis of SPOT multispectral HRV, LANDSAT MSS, ERS-1/SAR, aerial photographs and published maps of the ice cap and outlet glaciers of the King George Island, South Shetlands (Antarctica) covering a period of 36 years. Ice masses in this Island are relatively small, have a thermal regime that ranges from sub-polar to temperate and therefore may respond rapidly to temperature changes.

Examination of a SPOT multispectral composite allowed the identification of ice divides, drainage basins, glacier facies, crevassed areas and delimitation of the ice fringe. The transient snow line was identified at about 300-350 m above sea level. ERS-1/SAR images show marked returns of the ice divides and the limits of the ice cover, so being particularly useful for delimiting drainage basins. Satellite imagery when compared with aerial photographs taken in 1956 show that the ice fronts of some fast flowing outlet glaciers had retreat in average 800 to 1000 metres. General retreat, albeit in minor scale, seems to have occur in great part of the ice cap. Retreat of these glaciers occurred simultaneously to regional climatic warming during the last 50 years. Data derived from radio-echo sounding investigations, carried out by several nations along the last two decades, indicate that ice is covering a SE-NW trough in the centre of the Island where maximum ice thickness reaches 357 metres.

Keywords: South Shetlands, Glaciology, Sub-Polar Ice, Glacier Variations, Environmental Monitoring.

Los nombres geográficos utilizados por los autores no corresponden necesariamente a la toponimia oficial empleada en la República de Chile.

1. INTRODUCTION

The peripheries of the polar regions under the mean position of the arctic or antarctic atmospheric fronts, coupled with the limit of the sea extend, are some of the areas of the world most sensitive to environmental changes, showing a high variability of mean atmospheric temperature (Simões, 1990). Mean temperature for parts of the Antarctic Peninsula has recorded an increase of up to 1.3° C since 1960 (Peel et al., 1988). Further, ice caps in these regions are relatively small, have a thermal regime that ranges from sub-polar to temperate, and they may respond rapidly to environmental changes. These regions seem therefore to offer a good opportunity to assess and monitor the ice response to recent past and present environmental changes. A programme was initiated to evaluate the impact of these changes on the extend and dynamics of one of these ice masses (King George Island).

In this paper ERS-1/SAR, LANDSAT MSS, and SPOT HRV images are used together with 1: 27 000 scale aerial photographs to survey and monitor the main morphological and dynamic features of King George Island ice cover. We evaluate variations of the ice masses on the southern part of this island for all or parts of the period 1956 to 1992 (i.e. since the first aerial photograph survey by the former Falkland Islands Dependency Survey - FIDS, now the British Antarctic Survey - BAS). Radio echo-sounding studies carried out by BAS, the Russian Academy of Sciences (Govorukha et al., 1974) and a Sino-Uruguayan (Albert Lluberas, written communication) surveys provided for spotted ice thickness measurements, given a general notion about bedrock morphology.

King George Island, situated between 57° 35" and 59° 02" W, 61° 54" and 62° 16" S (Figure 1), is the largest of the South Shetlands. This island is approximately 79 km long (from Southwest to Northeast) and a maximum width of 27 km is reached just north of Admiralty Bay, an it is approximately 98% ice covered. On the south coast ice flows from a ridge of plateaus into large bays and inlets mainly through defined outlet glaciers and ice falls. The northern coast is skirted by ice cliffs and few outlet glaciers basins are well defined. Ice free areas are concentrated in small peninsulas in the southern part of the island where there is the highest concentration of stations in all Antarctica (9 stations). The interior of the ice cap is still relatively unexplored, and few glaciological studies have been carried out on this ice cover (e.g., Govorukha et al, 1974, Orheim and Govorukha, 1982). Topographic maps (Series BAS D501, Sheets W 62 56 and W 62 58/first edition - D.O.S. 610) show only general contours (at 200 m intervals) of the ice cover topography. Mean annual temperature for the region is about -2.8° C (Reynolds, 1981).

of 8.5 km² at Lago Guillermo. In the same figure a significant decrease in glacier width is also evident, which was almost 1 km on the eastern margin according to the 1994 GPS field survey. The glacier area along this margin has been reduced by more than 5 km² since 1981. This areal change is due to significant surface lowering occurring at lower parts of the glacier during the last decades, which may have increased recently. Field measurements of surface level on a transverse profile extending from the east margin to the medial moraine, carried out in 1990 and 1993 at the lower part of Upsala main terminus, gave an average thinning rate of 11 m/yr (Skvarca et al., 1995). This may be one of the greatest thinning rates recorded on earth during the last 30 years.

Figure 4 shows only a small section of the ERS-1/SAR image acquired on 22 January 1995, as well as the ice front positions at Brazo Upsala, derived from 1993 ERS-1 multitemporal data. Between 12 January, 16 February and 26 August the position of the glacier front fluctuated considerably. An advance, though non-uniform, took place along the eastern part while parts of the western lobe retreated. The same figure also shows a dramatic retreat due to a major calving event which occurred in mid 1994, revealed by comparison of ERS-1/SAR images of 26 August 1993 and 22 January 1995 as well as by the field survey in December 1994. From these two radar images the maximum retreat of 1.5 km is measured within the eastern part of the glacier terminus, decreasing towards west with the minimum retreat of 0.6 km. Close to the western margin, where the characteristic lobe-shaped front feature disappeared due to calving, the average recession was measured to be about 1 km. The ice-front position surveyed on 11 December 1994 and the terminus shown in the SAR image of 22 January, 1995, indicate that some retreat has also taken place during this short time interval.

The areal decrease in the frontal part during only 1.4 years, as computed from the latest two SAR images, is 3.35 km². Comparing this value to the 9.4 km² reduction occurred during previous 12 years, it is concluded that the glacier is presently by far at the highest retreating stage.

CONCLUSIONS

ERS-1/SAR data used in this study reveal not only the short- term fluctuations of the main terminus of Upsala Glacier through the analysis of 1993 multitemporal images but also document the drastic retreat which occurred mainly in mid 1994 and which was already detected and surveyed in the field during December 1994. The glacier frontal area has decreased by 3.35 km² in just 1.4 years time interval. The comparison to the areal losses during the previous 12 years indicates that the glacier has entered a dramatic retreat phase. Present results also show a significant reduction of almost 25 % in glacier width since 1981 for the lower part of the main glacier stream of Upsala, due to intense surface lowering.

Spaceborne SAR is a valuable tool for repeated monitoring of glacier regions frequently covered by clouds such as SPI. For this reason the visible satellite images available over this area are very limited. Continuous monitoring, possible now with high resolution SAR sensors, is of particular interest for glacier areas as described, where changes in areal and volume extent are presently occurring very rapidly. In view of these drastic glacier changes, the SAR imagery should be fully exploited for glaciological studies over both Patagonian Icefields where knowledge on basic glaciological characteristics is still very limited.

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REFERENCES

ANIYA, M., NARUSE, R., SHIZUKUISHI, M., SKVARCA, P. and CASASSA, G. 1992. ***Monitoring recent glacier variations in the Southern Patagonia Icefield, utilizing remote sensing data.*** *International Archives of Photogrammetry and Remote Sensing, Vol. XXIX, Part B7, (Proc. of XVIIth Congress of Internat. Society for Photogrammetry and Remote Sensing), 87-94.*

ANIYA, M. and SKVARCA, P. 1992. ***Characteristics and variations of Upsala and Moreno Glaciers, southern Patagonia.*** *Bulletin of Glacier Research, 10, 39-53.*

MALAGNINO, E. and STRELIN, J. 1992. ***Variations of Upsala Glacier in southern Patagonia since the late Holocene to the present.*** *In Naruse, R. and Aniya, M. (eds.) Glaciological Researches in Patagonia, 1990. 61-85.*

MANSILLA, L. 1994. ***Personal Communication,*** *Calafate, Argentina.*

NARUSE, R. and ANIYA, M. 1992. ***Outline of Glacier Research Project in Patagonia,*** *1990. Bulletin of Glacier Research, 10, 31-38.*

NARUSE, R. and ANIYA, M. 1995. ***Synopsis of glacier researches in Patagonia,*** *1993. Bulletin of Glacier Research, 13, 1-10.*

NARUSE, R., SKVARCA, P., KADOTA, T. and KOIZUMI, K. 1992. ***Flow of Upsala and Moreno Glaciers, southern Patagonia.*** *Bulletin of Glacier Research, 10, 55-62.*

ROTT H., MÄTZLER C., STROBL D., BRUZZI S. and LENHART K.G. 1988. ***Study on SAR land applications for snow and glacier monitoring.*** *ESA Contract No. 6618/85/F/FL(SC), Final Report, 186 p. & App.*

ROTT H. and NAGLER T. 1994. ***Capabilites of ERS-1/SAR for snow and glacier monitoring in alpine areas.*** *Proc. of Second ERS-1 Symposium ESA SP-361: 965-970.*

SKVARCA, P., SATOW, K., NARUSE, R. and J. C. LEIVA. ***Recent thinning, retreat and flow of Upsala Glacier, Patagonia.*** *Bulletin of Glacier Research, 13, 11-20.*

SKVARCA, P., ROTT, H. and MILLER, H. ***Proyecto "Investigaciones Comparativas de Sensibilidad Climática y Dinámica de Glaciares en Antártida, Patagonia y los Alpes",*** *(This volume).*

WARREN, C. R., GLASSER, N. F. and GREENE, D. R. ***Upsala Glacier, Patagonia: rapid calving retreat in freshwater.*** *Annals of Glaciology, 21 (in press).*

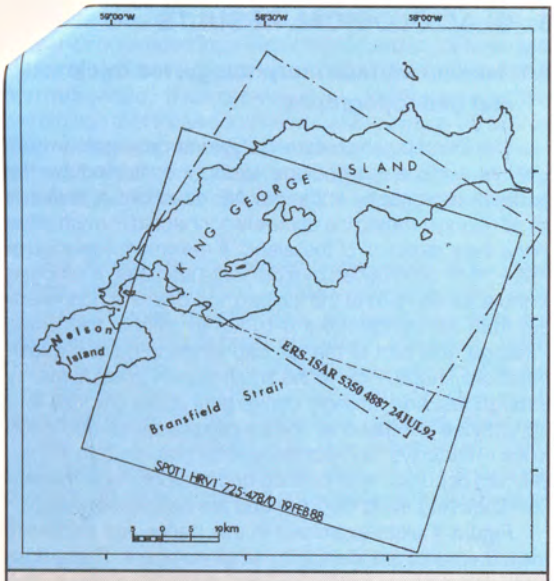

Figure 1 - Location Map for the main images (SPOT HRV XS 725-478 and ERS-1 / SAR 5350 48 87) discussed in this paper. Inset shows the location of King George Island.

We identify ice divides, drainage basins, glacier facies, crevassed areas and limits of the ice fringe for the southern part of the island. The northern part will be examined in a future paper based mainly on a SPOT HRV XS image acquired recently (March 1995).

2. DATA SOURCES AND METHODS

Table 1 below details the remote sensing information used in this study. Glaciological features of the King George Island ice cover were identified and marked on tracing paper over a print copy of a 1988 SPOT HRV XS image (KJ 725 478/0; Figure 2) at a scale 1: 100.000. Total error due to the resolution of the image and pen trace width is at the most 50 m.

Table 1. Details of satellite images, aerial photographs and radio-echo sounding (RES) surveys of King George Island, South Shetlands, examined in this study.

Data type	ID Number and path/row		Data imaged or surveyed
LANDSAT-3 MSS	30352-12171	232/103	20/Feb/79
LANDSAT-3 MSS	30352-12173	232/104	20/Feb/79
SPOT HRV XS		725-478	29/Feb/88
ERS-1 SAR PRI	5350 4887 TF PRI		24/Jul/92
FIDS aerial photographs			1956
Soviet RES survey	Oversnow		1970
BAS RES survey	Flight 38		1975
Sino-Uruguayan survey			1992

The preliminary map of glaciological features obtained from 1988 data was then manually compared with maps at the scale 1: 200.000 (Series BAS D501, Sheets W 62 56 and

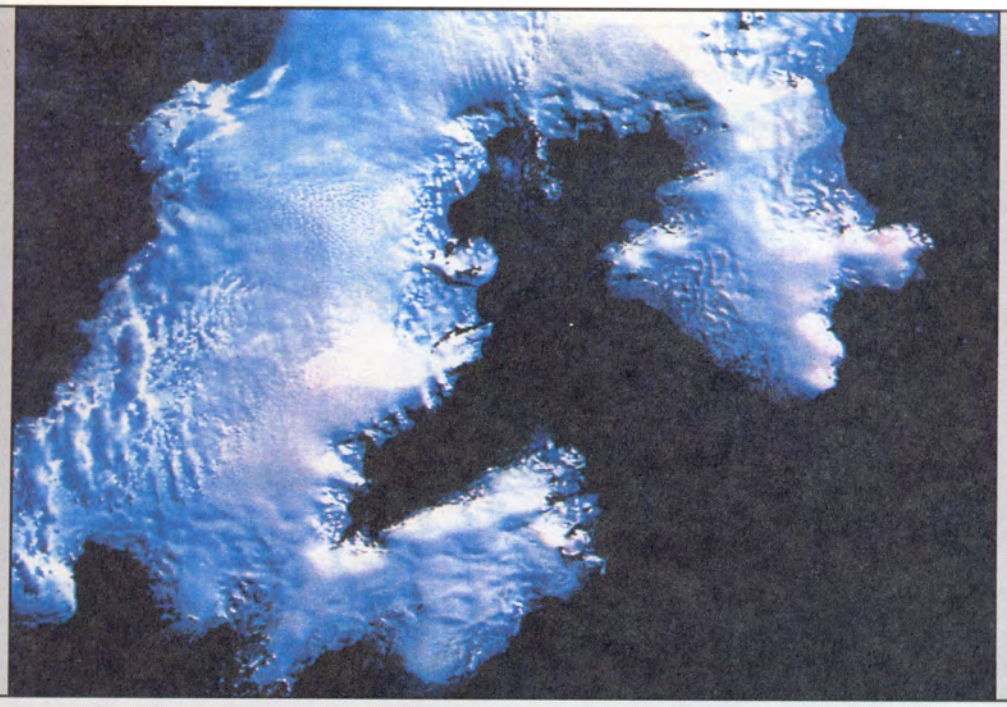

Figure 2 - SPOT HRV XS image (29 February 1988) of the southern part of King George Island. The scale is about 41 km across the image. The location of this image is shown in Fig. 1.

W 62 58/first edition - D.O.S. 610). These topographical maps were derived from an aerial photograph survey carried out during the austral summer of 1956/57 at the scale 1: 27 000 by FIDS. This is the oldest known remote sensing survey covering King George Island. For some selected outlet glaciers (e.g., Lange Glacier in Admiralty Bay) the original aerial photographs were examined to trace the ice front position in 1956/57 and surrounding rock outcrops. Maximum errors of 10 m are estimated for the traced positions, given a greater accuracy than those from the analysis of SPOT image print.

An ERS-1/SAR image (ID. 5350 4887 TF; Figure 3) print was provided by the Deutsche Forschungsanstalt Für Luft- und Raumfahrt - DLR. This product was obtained in precision code (PRI) form in an 1: 500 000 scale. Glaciological features (e.g., surface topography, snow and ice zones) identified in this radar image were compared with the interpretation of the SPOT image (see section 3). Finally, positive transparencies of LANDSAT Multispectral Scanner (MSS) products were also used in this study. The two images (ID. 232/103 e 232/104) were used to confirm the interpretation of the SPOT HRV and ERS-1 / SAR rather than to derive new information. The lower spatial resolution of the LANDSAT MSS means that surface details as crevasses are not easy identify and the error in the ice front determination is greater than the other two sensors.

Two RES oversnow surveys, by scientists from the former USSR in 1970 (radar frequency of 440 MHz; Govorukha et al., 1974) and a Sino-Uruguayan field work in 1991/92 (Albert Lluberas, written communication) provide some idea about bedrock topography and ice thickness. An airborne RES survey carried out by BAS in 1975 (Flight 38) provides for further data about ice thickness and bedrock morphology.

3. GLACIOLOGICAL RESULTS

3.1. Ice-cap surface morphology, ice thickness and bed topography

The ice cap, which extends over approximately 1313 km^2, its surface morphology strongly controlled by the bedrock topography in the SW-NE direction. A series of small non-symmetric ice domes is connected to each other in the main direction of the island. A maximum elevation of 700 ± 10 m, determined by a pressure altimeter, is reached in the southern part of the ice cap. Ice draining northwestern from the divide flows 8-10 km to cliffs in the Drake Passage, this part of the ice cap tends to have a quasi-parabolic shape. Flow to the southeastern coast is mainly through fast and strongly convergent outlet glaciers and abruptly ice falls that drain the ice cap plateau (at about 600 m a.s.l.) into bays. Some of these outlet glaciers (e.g. Lange Glacier) occupied well-defined depressions, have marked flow lines (e.g. King George) and are heavily crevassed.

Figure 4 plots examined in this paper. Ice thickness measurements are identify by small numbers. These data were derived from the three RES surveys cited above. The distribution of bedrock return seems to indicate that the summit of the ice cap is over a SW-NE sub-glacial ridge where ice thickness is only 86 metres. Ice thickness increases sharply to the West before decreasing when nearing the coast. It seems that a sub-glacial valley, which ice thickness frequently greater than 250 m, parallels this sub-glacial ridge. A maximum measured ice thickness of 357 metres is reached about 4 km from the divide. The absence of bedrock echoes returns for great part of the surveyed lines is not unexpected considering the high temperature of this ice cap (i.e. near the pressure melting

Figure 3 - PRI / SAR image (24 July 1992) of the southern part of King George Island. The scale is about 53.5 km across the image. The location of this image is shown in Fig. 1. © ESA (1992).

, the greater concentration of impurities (e.g., volca- ashes originated from Deception Island eruptions), and inhomogeneities (e.g., ice lenses associated with melting and refreezing, (Dowdeswell et al. 1984) came to the conclusion that these conditions make ice more "Clossy" to electro-magnetic energy. The presence of turbid melt-water plumes in front of several outlet glaciers reinforces the idea that at least part of the ice cap is at the melting point.

Ice divides are well marked in the visible (SPOT) and higher frequency (ERS-1 / SAR) reflecting very slow changes in slope direction and, as usual, they were not identified as any single break of slope (cf. Rees et al., 1993) during a 1993/94. Surface undulations transversal to the flow direction (wavelength of about 1 km) are observed in great part of the ice cap. This feature has been observed in other sub-polar ice caps (e.g., Dowdeswell et al., 1986) at the same spatial scale, and are attributed to interactions of changing snow facies and surface topography (Rees et al., 1993).

3.2. Outlet glaciers fluctuations

Comparison of the satellite images with the 1956/57 FIDS aerial photographs showed that ice fronts of some fast flowing outlet glaciers had retreated markedly during the period 1956-92. Lange Glacier (drainage basin of approximately 27,8 km^2) in Admiralty Bay retreated 1000 m in the period and losing an area of about 2 km^2, Wit Stwosz Glacier in Kraków Peninsula retreated about 800 m. General retreat, albeit in minor scale, is recorded at least for another nine fronts in this ice cover (cf. Figure 4). Exception seems to have occur in parts of the northern coast (e.g. Usher Glacier), but lack of ground control (they are few rock outcrops near this glacier) for this part of the island makes detection of changes more difficult. Other glaciers may have oscillated at a scale lower than the estimated error limit for the used method (i.e. ± 50 m).

It is tempting to attribute this general ice front retreat to the recorded regional climatic warming (cf., Section 1). Similar ice front changes were observed in other South Shetland Islands (e.g., Livingston Island; Calvet et al., 1992). However this assumption should be considered with care, glacier response to environmental changes may take decades to centuries. We may be observing the result of changes along the last centuries and other process may be also involved. For example, a glacier surge is followed by a long quiescent period when ice stagnation and thinning occur resulting in terminus retreat. No surges, however, have been observed in the South Shetlands and the examined glaciers do not show evidences for this kind of phenomena.

3.3. Surface reflectance, snow/ice facies and transient snow line position

Examination of the SPOT multispectral composite, acquired in late February, allowed the identification of a limit for two facies at the surface (ground truth carried out in the summer of 1993/94): (1) A snow facies characterised by a high surface reflectance which is tentatively attributed to a "snow facies" including the percolation and wet snow (soaked) zones (following the terminology by Benson, 1962). Shallow cores carried out by authors in the 93/94 summer seems to indicate that the summit of the ice cap is in the percolation zone; (2) "ice facies" including ablation and superimposed ice zones. This area of the ice cap is characterised by a lower surface reflectance mainly due to high content of dust in the ablation zone (including a great concentration o volcanic dust, probably originated from Deception Island eruptions). The limit between the two zones was interpreted as the position of the transient snow line at the end of the summer (at about 300 to 350 m a.s.l.). A ground survey observed that the snow-line altitude rose to 450 m by the end of the 1994/95 melting season (March).

Examination of SAR image, acquired in mid-winter, also allows the identification of two zones: (1) a zone of low backscatter at lower elevations (near the coast) and (2) a zone of high backscatter at higher elevations. However these zones do not coincide with the ones determined from the SPOT image. Taking in consideration that the SAR image was taken in mid-winter, so there is a snow-cover even over great part of the ablation area of the ice cap, we suggest the following interpretation for the two zones (following Rees et al., 1993): (1) a zone where bare ice, albeit covered thinly by winter snow, results in specular scattering away from the radar; (2) an upper zone where wet snow gives high backscatter in a different direction reducing backscattering.

4. CONCLUSIONS AND FUTURE WORK

An outline the main features of the King George Island ice cover were obtained through the examination of satellite, air photographs and RES data. Previously to this study little was known about ice morphology and dynamics, glacier termini, and ice thickness. Ice cover morphology is strongly controlled by bedrock structure in the SW-NE direction. Ice reaches a maximum altitude of 700 ± 10 m and a maximum measured ice thickness of 357 m. Very few RES returns seem to indicate that at least part of ice is near or at the pressure melting point, a conclusion reinforced by the great number of melt-water plumes in front of the glaciers termini. RES surveys in other frequencies may give a better idea about ice thickness distribution.

Eleven outlet glaciers termini retreated hundreds of metres to 1 km (e.g., Lange Glacier in Admiralty Bay) during the period 1956-1992. These changes in the frontal position of glaciers are, probably, a response to regional climatic warming but further studies are necessary to confirm this hypothesis. At the end of the melting season (March) transient snow line is found, in general, at about 300-350 m a.s.l.. By the end of the 1994/95 summer, however, it rose to 450 m.

Examination of a SPOT multispectral composite allowed the identification of two zones (or facies) at the snow surface. They are attributed to different reflectance for a snow facies (percolation and wet snow zones) and an ice facies (ablation and superimposed zones). Two superficial zones were also identify in an ERS-1 / SAR image but they do not coincide with the SPOT zones. The SAR image zones result from differences in backscattering. Probably, an upper zone formed by wet zone results in high backscattering and a lower zone (characterised by bare or thinly snow covered ice) results in high scattering away from the radar.

Finally, a SPOT/HRV image acquired in March 1995 will allow the study of the relatively unexplored northern part of the island.

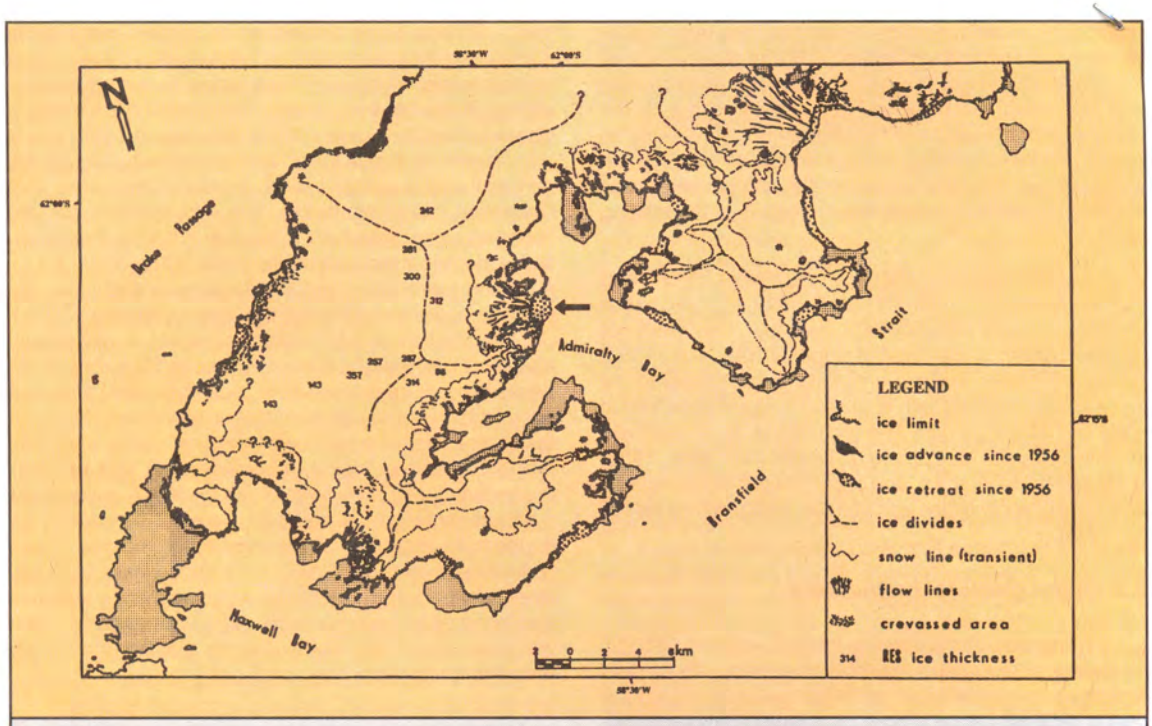

Figure 4 - Glaciological interpretation for the remote sensing data described in this paper. See text for discussions and data source. Arrow indicates Lange Glacier that retreated about 1 km in the period 1956-92.

5. ACKNOWLEDGEMENTS

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REFERENCES

BENSON, C. C. 1962. **Stratigraphic studies in the snow and firn of the Greenland ice sheet.** *U.S. Snow, Ice, and Permafrost Research Establishment Research Report, No. 70. 93 pp.*

CALVET, J., CORBERA, J. and FURDADA, G. 1992. **Variacion del frente glaciar en Bahia Sur y Punta Siddons entre 1956 y 1991, Isla Livingston, Islas Shetland del Sur.** *In: López-Martínez (ed.). Geología de la Antártida Occidental. Simpósios. III Congreso Geológico de España y VIII Congresso Latinoamericano de Geología. Salamanca, España. p. 283-292.*

DOWDESWELL, J. A. et al. 1984. **Airborne radio echo sounding of sub-polar glaciers in Spitsbergen.** *Norsk Polarinstitutt Skrifter. No. 182. 41 pp.*

DOWDESWELL, J. A. et al. 1986. **Digital mapping of the Nordaustlandet ice caps from airborne geophysical investigations.** *Annals of Glaciology, v 8, p. 51-58.*

GOVORUKHA, L. S., CHUDAKOV, V. I. e SHALYGIN, A. M. 1974. **Radio echo sounding of King George Island (Waterloo) ice cap.** *Sovetskaya Antarktischeskaya Ekspeditsiya Informatsionnyy Byulleten, v. 89, p. 15-18.*

ORHEIM, O. and GOVORUKHA, L. S. 1982. **Present-day glaciation in the South Shetland Islands.** *Annals of Glaciology, v. 3, p. 233-238.*

PEEL, D. A., MULVANEY, R. and DAVISON, B. M. 1988. **Stable-isotope/air-temperature relationships in ice cores from Dolleman Island and the Palmer Land Plateau, Antarctic Peninsula.** *Annals of Glaciology, v. 10, p. 130-136.*

REES, W. G., DOWDESWELL, J. A. and DIAMENT, A. D. 1993. **Investigations of arctic ice-sheets and glaciers using ERS-1/SAR.** *In: Proceedings First ERS-1 Symposium Space at the Service of our Environment, France, November 1992. p. 263-268.*

REYNOLDS, J. M. 1981. **The distribution of mean annual temperatures in the Antarctic Peninsula.** *British Antarctic Survey Bulletin, No. 54, p. 123-133,*

SIMÕES, J. C. 1990. **Environmental interpretation from Svalbard ice cores.** *University of Cambridge, Unpublished Ph. D. thesis. 238 pp.*