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Study of Johnsons Glacier (Livingston Island, Antarctica) by means of shallow ice cores and their tephra and by analysis of ^{137}Cs content

Estudi de la glacera de Johnsons (Illa de Livingston, Antàrtida) per mitjà de sondejos de gel poc profunds i del seu contingut en cendres volcàniques i en ^{137}Cs

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ABSTRACT

With the aim of monitoring the dynamics of the Livingston Island ice cap, the Departament de Geodinàmica i Geofísica of the Universitat de Barcelona began yearly surveys in the austral summer of 1994-95 on Johnsons Glacier. During this field campaign 10 shallow ice cores were sampled with a manual vertical ice-core drilling machine. The objectives were: i) to detect the tephra layer accumulated on the glacier surface, attributed to the 1970 Deception Island pyroclastic eruption, today interstratified; ii) to verify wheter this layer might serve as a reference level; iii) to measure the ^{137}Cs radio-isotope concentration accumulated in the 1965 snow stratum; iv) to use the isochrone layer as a mean of verifying the age of the 1970 tephra layer; and, v) to calculate both the equilibrium line of the glacier and average mass balance over the last 28 years (1965-1993). The stratigraphy of the cores, their cumulative density curves and the isothermal ice temperatures recorded confirm that Johnsons Glacier is a temperate glacier. Wind, solar radiation heating and liquid water are the main agents controlling the vertical and horizontal redistribution of the volcanic and cryoclastic particles that are sedimented and remain interstratified within the glacier. It is because of this redistribution that the 1970 tephra layer does not always serve as a very good reference level. The position of the equilibrium line altitude (ELA) in 1993, obtained by the ^{137}Cs spectrometric analysis, varies from about 200 m a.s.l. to 250 m a.s.l. This indicates a rising trend in the equilibrium line altitude from the beginning of the 1970s to the present day. The varying slope orientation of Johnsons Glacier relative to the prevailing NE wind gives rise to large local differences in snow accumulation, which locally modifies the equilibrium line altitude. In the cores studied, ^{137}Cs appears to be associated with the 1970 tephra layer. This indicates an intense ablation episode throughout the sampled area (at least up to 330 m a.s.l), which probably occurred synchronically to the 1970 tephra deposition or later. A rough estimate of the specific mass balance reveals a considerable accumulation gradient related to the increase with altitude.

Key words: Antarctica. Glacial dynamics. Tephra layers. Shallow ice cores. ^{137}Cs spectrometry. Equilibrium line altitude. Specific mass balance.

RESUM

Amb l'objectiu de monitoritzar la dinàmica del casquet glacial de l'Illa de Livingston, el Departament de Geodinàmica i Geofísica de la Universitat de Barcelona va iniciar campanyes de mesura anuals a la glacera de Johnsons durant l'estiu austral de 1994-95. Durant aquesta campanya de camp es van dur a terme 10 sondejos de gel poc profunds, amb recuperació de testimoni continu, mostrejats verticalment amb una sonda manual. Els objectius eren detectar la capa de cendres volcàniques dipositades a la superfície de la glacera, que s'atribueixen a l'erupció piroclàstica de l'illa Decepción de 1970, actualment interestratificada, verificar si aquesta capa pot ser utilitzada com a nivell guia, identificar l'horitzó enriquit en el radioisòtop ^{137}Cs acumulat en l'estrat de neu corresponent a l'any 1965, actualment també interestratificada, utilitzar aquest nivell isòcron per comprovar la datació de la capa de cendres de 1970 i calcular la línia d'equilibri de la glacera i el seu balanç de massa mitjà per als últims 28 anys (1965-1993). L'estratigrafia dels testimonis de gel dels sondejos, les seves corbes de densitat acumulada i les temperatures quasi isotermes del gel enregistrades confirmen que la glacera de Johnsons és temperada. El vent, l'escalfament produït per la radiació solar i l'aigua líquida són els agents principals que controlen la redistribució horitzontal i vertical de les partícules, tant volcàniques com crioclàstiques, que sedimenten a la superfície de la glacera i hi romanen interestratificades. Per causa d'aquesta redistribució, la capa de cendres no sempre és un bon nivell de referència. La posició altitudinal de la línia d'equilibri (ELA) el 1993, obtinguda de l'anàlisi per espectrometria del radioisòtop ^{137}Cs, varia des de 200 m s.n.m fins a 250 m s.n.m. Això implica un ascens en l'altitud de la línia d'equilibri des de l'inici de la dècada de 1970 fins a l'actualitat. La diferent orientació dels vessants de la glacera de Johnsons respecte als vents predominants del NE provoca importants diferències locals en l'acumulació de neu que, localment, fa variar l'altitud de la línia d'equilibri. Als testimonis de gel estudiats el ^{137}Cs sempre es troba associat a les partícules de la capa de cendres de 1970. Això implica l'existència d'un important episodi d'ablació en tota l'àrea mostrejada (com a mínim fins a una altitud de 330 m s.n.m.) que es va produir sincrònicament al dipòsit de la capa de cendres de 1970 o amb posterioritat. Una estimació a grans trets del balanç de massa indica un elevat gradient d'acumulació en funció de l'increment d'altitud de la glacera.

Paraules clau: Antàrtida. Dinàmica glacial. Capes de cendres volcàniques. Sondejos de gel superficials. Espectrometria del ^{137}Cs. Altitud de la línia d'equilibri. Balanç de massa específic.

INTRODUCTION

Livingston Island forms part of the Antarctic shore area, which is particularly sensitive to climatic variation (Mitchell et al., 1990). Johnsons Glacier drains part of the Hurd Peninsula ice cap (south-east of Livingston Island). Its basin covers an area of about 5 km^2 in which two main flow lines of different slope and length converge on a 50-m-high ice cliff, extending 500 m along the coast. The first flow line (Dorotea) is 2,150 m long with a mean slope gradient of approximately 6º towards the North; the second flow line (Johnsons) is 980 m long with a mean gradient of approximately 10º towards the West. Dorotea and Johnsons divides are at elevations of 330 and 270 m a.s.l. respectively.

With the aim of monitoring the dynamics of Johnsons Glacier, the Departament de Geodinàmica i Geofísica of the Universitat de Barcelona began yearly surveys in the austral summer of 1994-95 on this glacier (Fig. 1). During this field campaign, 10 shallow ice cores were sampled in order to detect the 1970 interestratified tephra layer and the ^{137}Cs radio-isotope concentration accumulated in the 1965 snow stratum.

Several Holocene volcanic ash-layers, 0.5-2 cm thick, can be found interstratified in the glacial ice. Due to its proximity it is assumed that the origin of the volcanic ash is Deception Island (Calvet et al., 1993; Casas et al., 1998). The uppermost tephra layer corresponds to the 1970 pyroclastic eruption that covered the eastern part of Livingston Island (Baker and McReath, 1971). The ashes constitute an excellent marker of the internal structure and stratigraphy of the ice and, when dated, they provide valuable information about ice age and mass balance (Calvet et al., 1993; Casas et al., 1998).

Furthermore, a series of atmospheric thermonuclear tests conducted between 1953-1980, mostly in the Northern Hemisphere, injected large quantities of artificial radionuclides into the upper atmosphere and stratosphere. These radionuclides were transported from their sources over Antarctica (Pourchet et al., 1997). ^{137}Cs is one of these artificial fission products. The first significant increase in ^{137}Cs content in Antarctica was observed in January 1955 (Piccioto and Wilgain, 1963), corresponding to the radionuclides released in the Yvi and Castle series tests conducted in 1953. The highest recorded activity corresponds to 1965 and in all likelyhood was caused by the stratospheric transfer of debris from the Dominic and USSR test series (Crozaz, 1969; Pourchet et al., 1997).

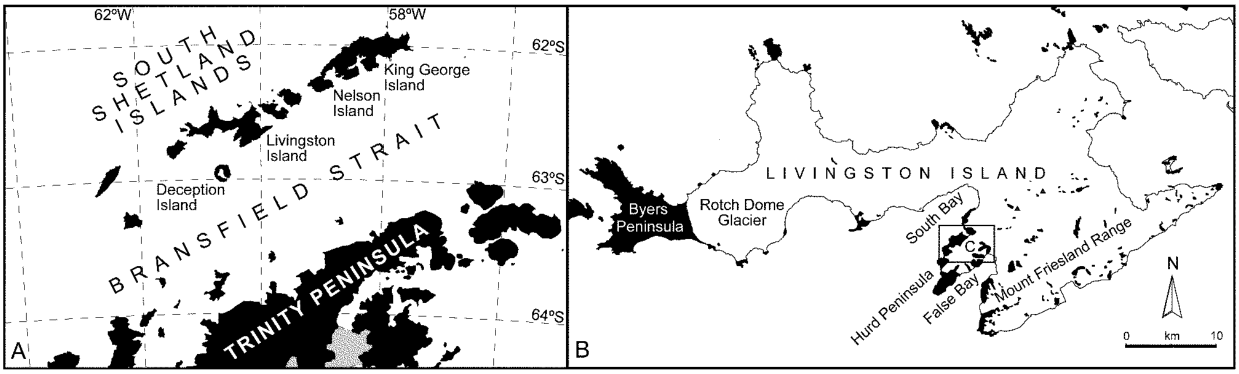

Figure 1.: Regional setting of the study area. A: South Shetland Islands; B: Livingston Island; C: Study area which includes Johnsons Glacier.

Figura 1: Situació regional de l'àrea d'estudi. A: Illes Shetland del Sud; B: Illa Livingston; C: Àrea d'estudi que inclou la glacera de Johnsons.

As the arrival and fall-out dates are clearly documented, ^{137}Cs accumulations serve as characteristic isochrone reference levels in snow and are currently used in glaciological studies to determine the average rate of snow accumulation or specific mass balance in glacier accumulation locations (Pourchet et al., 1997).

The objectives of the ice core sampling and analysis were: first, to verify whether the 1970 tephra layer interstratified within the ice cores could be clearly found and might serve as an isochrone reference level; second, to determine the 1965 ^{137}Cs level, and then to use this isochrone level to verify the age of the 1970 tephra layer and to calculate both the equilibrium line of the glacier and the snow accumulation rate or average specific mass balance over the last 28 years (1965-1993).

METHODS

The ^{137}Cs (30,2 years half-life), unlike to other radionuclides such as natural ^{210}Pb, ^{3}H or ^{85}K, is not dissolved and easily entrained by snow meltwater. It remains fixed to the aerosols in the atmosphere and, after fall-out, to the solid particles contained within the snowpack (Pourchet et al., 1994). As a result of solar radiation heating these particles penetrate and accumulate a few decimetres below the summer snowpack or ice surface (Pourchet, pers. com.). The most active ^{137}Cs accumulation corresponds to the year 1965.

In glacial accumulation zones, the 1965 layer, rich in ^{137}Cs, was buried by snowfalls during successive winter seasons. Consequently, in Johnsons Glacier, we expected to find the ^{137}Cs layer several meters below the 1970 tephra layer in the accumulation zone. On the downward side of the equilibrium line, which separates accumulation and ablation zones in the glacier, the ^{137}Cs layer is unburied because of the effects of ablation. However, the particles with the fixed ^{137}Cs remain about 60 cm to 100 cm below the summer ice surface. Even though the equilibrium line altitude (ELA) varies slightly each year, finding ^{137}Cs at a depth of about 1 m gives a good approximation of the transition between the accumulation and ablation

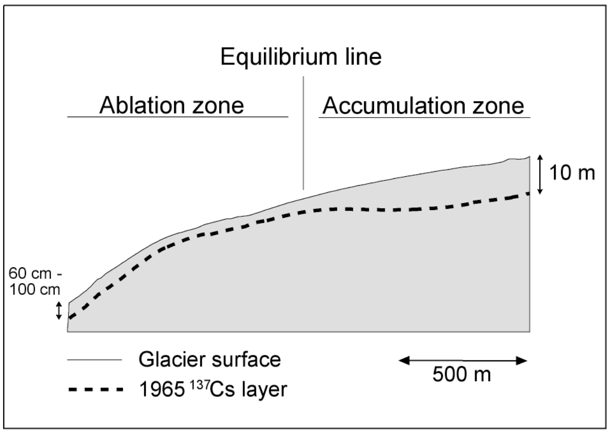

Figure 2: Schematic representation of the probable location of the ^{137}Cs accumulation layer.

Figura 2: Representació esquemàtica de la probable localització de l'horitzó d'acumulació de ^{137}Cs.

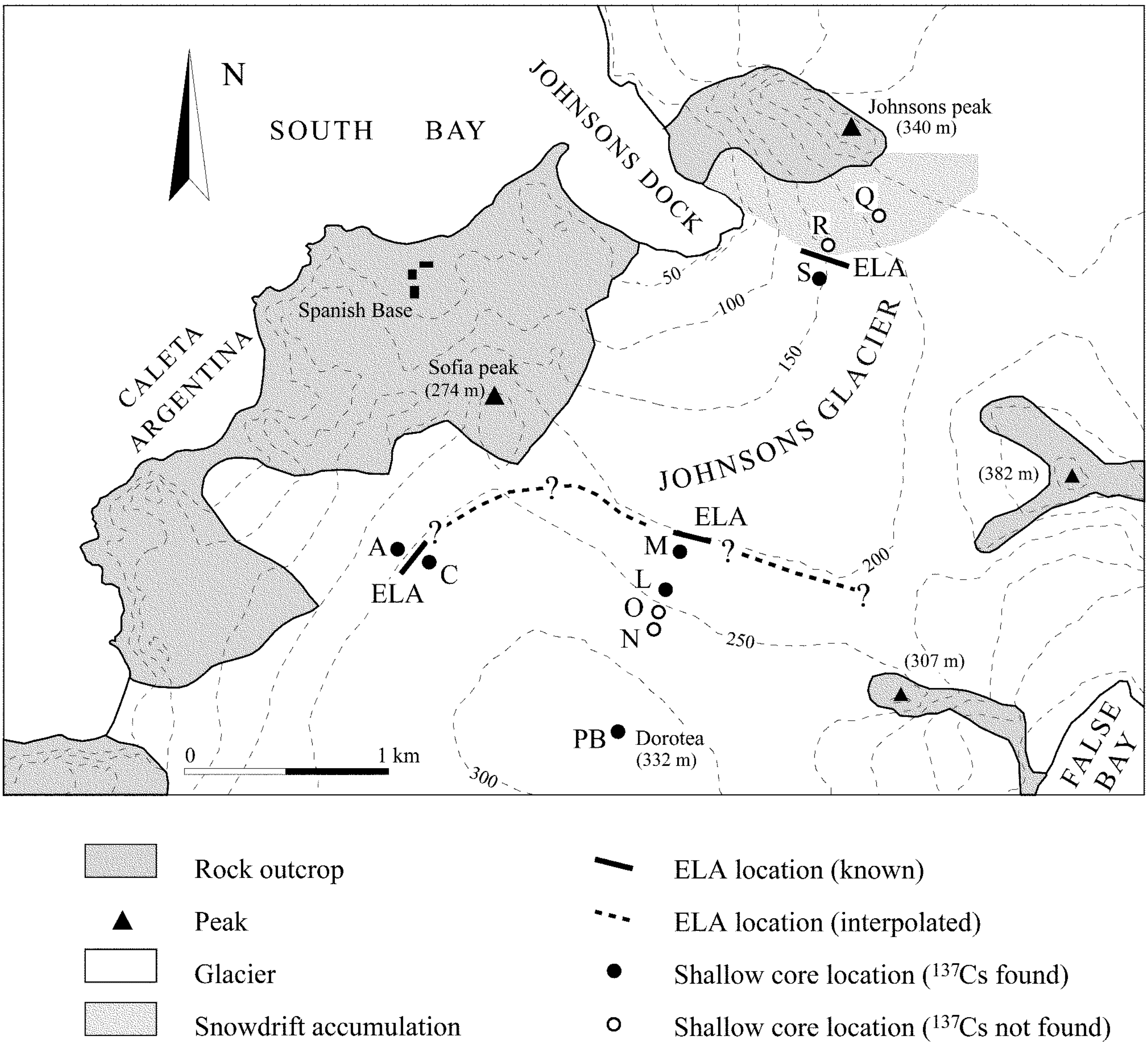

Figure 3: Shallow ice cores in Johnsons Glacier and location of the equilibrium line as deduced from the ^{137}Cs core analysis.

Figura 3: Situació dels sondejos de gel a la glacera de Johnsons i localització de la línia d'equilibri deduïda de l'anàlisi del contingut en ^{137}Cs dels testimonis de gel.

zones (Fig. 2). In order to estimate the ELA, 10 shallow ice cores ranging from depths of 0.5 to 16 m and with a diameter of 7 cm were obtained with a manual vertical ice-core drilling machine (Photo 1) in the study area (Fig. 3).

The ice-cores obtained were described, cut into fragments of approximately 30 cm in length, weighed and packed for transport. In the laboratory, the ice-core samples were melted and acidified, and the radio-isotopes were extracted using ion-exchange filters (Delmas and Pourchet, 1977). Dust and volcanic ashes were also retained in the filters.

In order to identify the ^{137}Cs content, the filters were analysed by gamma spectrometry using a specially designed low-background scintillation detector (Pinglot and Pourchet, 1994) in the Laboratoire de Glaciologie et Géophysique de l'Environnement (CNRS, Grenoble).

Photo 1: Manual vertical ice-core drilling machine. The ice-cores are extracted in fragments of less than 1 m in length.

Foto 1: Sonda manual per a sondejos verticals al gel. Els testimonis de gel són extrets en fragments inferiors a 1 m.

From the ice core description and analysis, we obtained several results about the textural and physical characteristics of the glacier, tephra distribution and ^{137}Cs accumulation.

FIRN AND GLACIAL ICE TEXTURAL AND PHYSICAL CHARACTERISTICS

No seasonal succession could be identified from the core stratigraphy. The same conclusion was reached by Ren et al. (1995) in Nelson Island (South Shetland). Neither representative cycles nor a clear succession of snow, firn and glacial ice were found within the cores. The cores showed a few fine grain layers, common round grain layers (grains 2-3 mm in diameter), and a considerable number of compact ice layers. There were also many ice nodules due to melting, percolation and the refreezing of water (Photo 2). These layers ranged from 1-2 mm to several decimetres in thickness. Ice layers containing air bubbles were isolated only in three ice cores. The structure and distribution of the ice layers imply melting and refreezing, causing the different former layers to mix. It was assumed that the top of the first ice layer that was thicker than 3 cm corresponded to the end of the previous melting season or 1993-94 summer. No stratigraphic correlation could be established between the different cores.

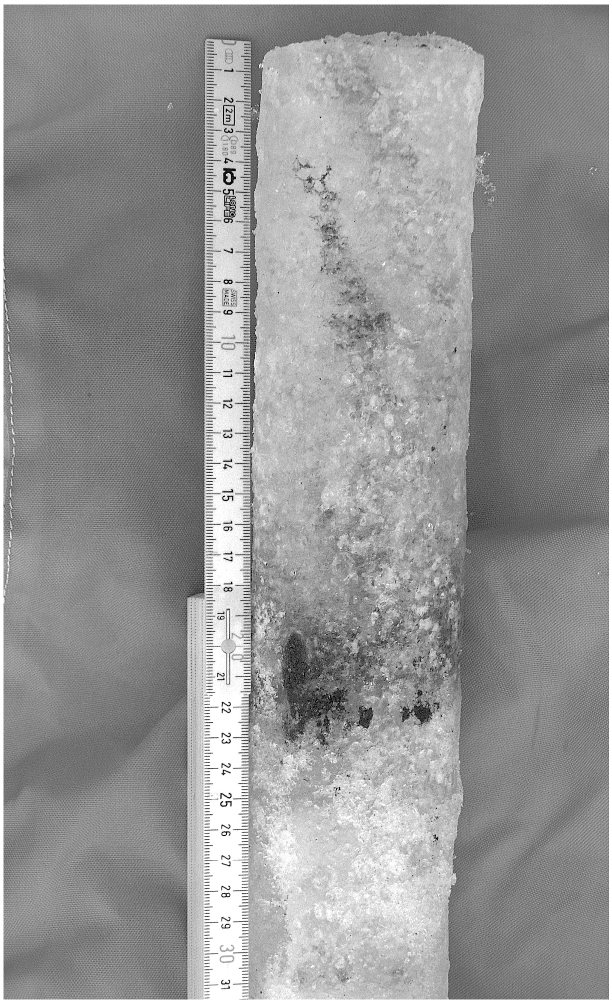

Photo 2: Fragment of a 7-cm diameter ice-core. It shows an interstratified tephra layer and a percolation that affected and included volcanic particles.

Foto 2: Fragment d'un testimoni de gel de 7 cm de diàmetre. Mostra una capa de cendres volcàniques interestratificades i percolacions que inclouen partícules volcàniques.

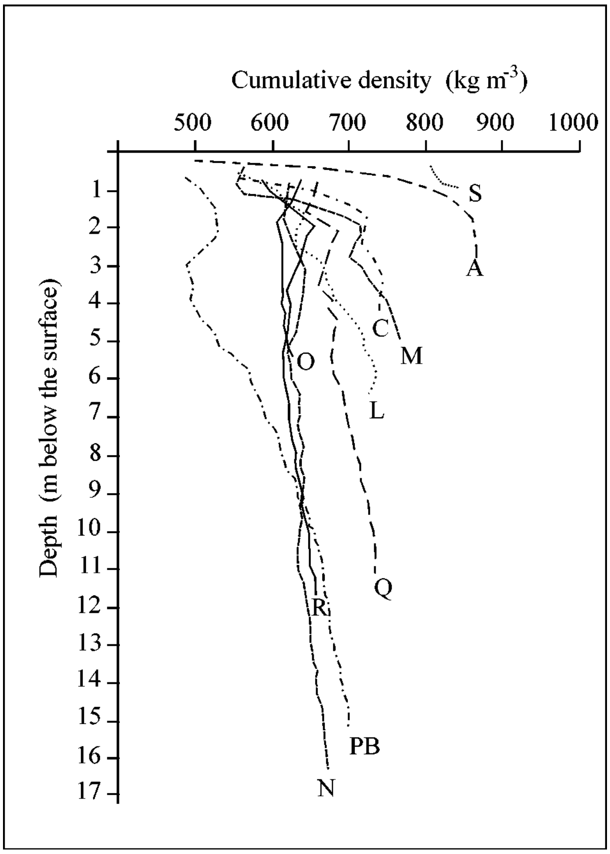

Figure 4: Cumulative density of the 10 ice cores. The cumulative density for a depth z is the density between the surface and z. The letters correspond to the drilling locations and the same lettes are used on the maps, in the other figures and in the text. A cumulative density curve valid for the 10 locations cannot be drawn.

Figura 4: Densitat acumulada dels 10 testimonis dels sondejos de la glacera de Johnsons. La densitat acumulada en una profunditat z és la densitat del gel entre la superfície i la profunditat z. Les lletres corresponen als punts dels sondejos i a les mateixes lletres als mapes, a les altres figures i al text. No s'ha pogut establir una única corba de densitat acumulada vàlida per als 10 punts mostrejats.

The density of the different segments of the cores ranged from 391 kg m^{-3} to 962 kg m^{-3}. The most frequent values ranged between 600 - 800 kg m^{-3} and varied for the different cores depending on the proportion of compact ice layers.

The cumulative density for a depth z is the density between the surface and z. Except for the superficial accumulations (1-2 m), in cold glaciers such as in Terre Adélie the cumulative density tends to approximate to a curve that is valid for the different sample points. The cumulative density curves reflect the increasing compaction of the firn with depth (Pettre et al., 1986). Cumulative densities for the 10 ice-cores taken from Johnsons Glacier are plotted in figure 4. Taking into consideration the spatial distribution of the ice cores (Fig. 3) no correlation can be established between the different cumulative density curves. As a result, a cumulative density curve with validity for all the sample locations cannot be drawn due to the varying proportion of compact ice layers in the ten ice-cores. The implication of this is that a regular densification pattern along the glacier does not exist. This is in accordance with the finding mentioned above that no stratigraphic correlation could be established between the different cores.

A temperature sensor set was placed into the 15,2 m deep ice-core hole PB (Fig. 3) immediately after perforation. It was isolated from direct atmospheric influence by means of a plastic plug, about 25 cm thick placed at the top of the perforation hole. This method has proved to be adequate for detecting ice temperature diferences of a few degrees in cold glaciers (Pourchet, com. pers.). The ice temperatures recorded every meter ranged from -0,1ºC to -0,3ºC, showing an isotherm profile. All these data are consistent with the observations of López-Martínez et al. (1992) and with the definition of a temperate glacier.

THE TEPHRA LAYERS

As described above, several volcanic ash-layers can be found interstratified within the glacial ice and can be easily identified in the ice cliffs hanging over the sea. We expected to sample the upper tephra layer, corresponding to 1970 Deception Island pyroclastic eruption (Baker and McReath, 1971), when extracting the ice cores.

The rock outcrops not covered by the glacier are affected by cryoclastic processes. The resulting millimetric particles are transported and redistributed by the wind over the glacier. Sometimes they accumulate to form discontinuous layers with a thickness of several mm. In most cases, volcanic ash is mixed with these rock particles, but because of their small sizes it is difficult to distinguish between the two. Layers constituted by tephra, pyroclastic and mixed particles were found in the ice cores.

The particles were not always concentrated in thin, well-defined layers. The layers varied greatly in thickness

(3 mm to 2 cm). There were also zonations of particles or else they were diffused along several decimetres of ice (Fig. 5).

If we consider the source location and the distance of transportation Johnsons Glacier is small and there are no major obstacles capable of disturbing the pyroclastic sedimentation. This suggests that pyroclastic accumulation at the time of deposition was probably quite homogeneous throughout the study area, unlike that found in the ice-cores. The horizontal and vertical redistribution of the particles can be accounted for the following three mechanisms, which can affect both pyroclasts and cryoclastic particles:

1.- Just after deposition, the wind can erode, transport and resediment particles depending on the small topographic irregularities in the glacier surface. The result is a tephra layer with an irregular thickness. This mechanism results in an horizontal redistribution of the sediment.

2.- The volcanic particles are heated by solar radiation and penetrate to a depth of a few centimetres to decimetres below the ice surface. As a result, particles are redistributed and diffused vertically within the ice (Fig. 5).

3.- During summer there is plenty of liquid water from the snowcover thaw. Locally the water saturates the snowcover, percolates through its irregularities and the ice cracks and runs over the surface generating supraglacial streams. Percolations redistribute particles vertically (Photo 2), and supraglacial streams can erode the fine fraction or the complete thepra layer.

Between 1 and 8 different particle accumulation levels were identified in the ice cores. At drilling location N (Fig. 3) there were 8 levels of particle accumulation, but none of them was dated as the 1970 tephra layer. It would seem that these levels are related to wind transport of cryoclastic particles and might correspond to thin layers of snow drifts deposited just after a slope rupture (Mases, 1997).

At some locations the 1970 tephra layer was clear and readily identifiable but in others it was not the case, so the 1970 tephra layer does not always serve as a good reference level. However, in most cases, the layer corresponding to the 1970 pyroclastic eruption was eventually dated in relation to the 1965 ^{137}Cs accumulation isochrone, as explained below.

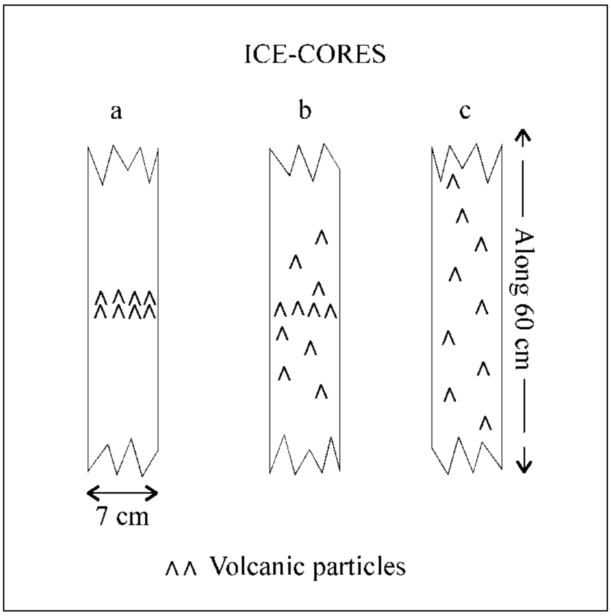

Figure 5: Distribution of the volcanic and other rock particles within the ice-cores: a: well-defined tephra layers (0.3-2 cm); b: zonation of the volcanic particles; c: volcanic particles diffused along about 60 cm. (Letters do not correspond to drilling locations).

Figura 5: Distribució de partícules volcàniques i d'altres tipus en els testimonis de gel: a: capa de cendres ben definida (0,3-2 cm); b: zonació de les partícules volcàniques; c: partícules volcàniques difoses al llarg d'uns 60 cm. (Les lletres no es corresponen amb la localització del sondejos).

^{137}CS CONTENT

The results of the ice-core samples analysis are summarised in Table 1. The ^{137}Cs was not detected in four of the ten ice cores, so the ^{137}Cs accumulation layer does not always exist. On the other hand, we observed that in those ice cores in which ^{137}Cs was detected, it always appeared in association with the 1970 tephra particles. As explained in the previous section, different particle layers were found in the ice cores. When these layers were not associated with the radioisotope ^{137}Cs, we assumed them to be cryoclastic particle layers quite unrelated to the 1970 tephra deposition.

In four of the cores the ^{137}Cs accumulation layer was not found, probably for different reasons. The cores Q and R were drilled in a hectometric snowdrift accumulation area (Vilaplana and Pallàs, 1993; Ximenis et al., this volume) generated by the prevailing Northeast winds (Ro-

Drilling location	Altitude (m a.s.l.)	Total depth(cm)	Winter str. (cm)	^{137}Cs depth(cm)	Cum.ρ (kg m^{-3})	Tephra/P (cm w.e.)	^{137}Cs (cm w.e.)	Act. ^{137}Cs (Bq cm^{2})	Balance/y (cm w.e.)
C	**265**	**414**	**38**	**268**	**800**	**214-215**	**215**	**22**	**6.3**
A	**245**	**274**	**0**	**36**	**650**	**23-29**	**23**	**12**	**0.8**
PB	**331**	**1525**	**63**	**1022**	**660**	**671**	**671**	**102**	**21.7**
N	261	1622	80	-	-	410-413	-	0	-
O	252	529	61	-	-	110-111	-	0	-
L	**242**	**640**	**60**	**395**	**680**	**270**	**270**	**12**	**7.5**
M	**213**	**484**	**61**	**122**	**620**	**77**	**77**	**22**	**0.6**
Q	212	1105	45	-	-	280-286	-	0	-
R	155	1165	59	-	-	192-194	-	0	-
S	**148**	**94**	**0**	**3**	**800**	**2**	**0**	**204**	**0**

Table 1: Main data recorded from the 10 shallow ice cores. The ice cores where ^{137}Cs was detected are highlighted in bold. The drilling location letters correspond to the same letters on the maps, in the other figures and in the text: C, A in the Caleta Argentina area; PB, N, O, L, M along the Dorotea flow line; Q, R, S in the Johnsons area and flow line; Altitude: altitude of the drilling location above sea level; Total depth: total depth of the hole or total length of the ice core; Winter str.: thickness of the surface snow stratum at the time of sampling, measured in cm, precipited during the previous winter; ^{137}Cs depth: distance from the surface down to the ^{137}Cs layer, or length of the ice core down to the ^{137}Cs layer, measured in cm; Cum. r: cumulative density or density between the surface and the ^{137}Cs level; Tephra/P: depth of the most representative volcanic ash-layers or particle layers transformed to their water equivalent value (accumulated density x length of the core; the length of the core corresponds to its depth with minor corrections introduced during field work); ^{137}Cs: depth of the ^{137}Cs accumulation layer transformed to their water equivalent value; Act. ^{137}Cs: ^{137}Cs total activity corrected for decay to the deposition time; Balance/y: mean annual specific mass balance for the 1965-1993 period, in cm of water equivalent per year.

Taula 1: Principals dades obtingudes dels 10 testimonis de gel dels sondejos superficials. Els testimonis en què es va detectar ^{137}Cs es resalten en negreta. Les lletres corresponents a les localitzacions dels sondejos corresponen a les mateixes lletres al mapa, a les altres figures i al text: C, A a l'àrea de Caleta Argentina; PB, N, O, L, M al llarg de la línia de flux Dorotea; Q, R, S a l'àrea i la línia de flux de Johnsons; Altitude: altitud del lloc del sondeig sobre el nivell del mar; Total depth: profunditat total del sondeig o longitud total del testimoni de gel; Winter str.: gruix de l'estrat superficial de neu al moment del mostreig, mesurat en cm, precipitat durant l'hivern anterior; ^{137}Cs depth: distància des de la superfície fins al nivell de ^{137}Cs, o longitud del testimoni de gel fins al nivell de ^{137}Cs, mesurat en cm; Cum. r: densitat acumulada o densitat entre la superfície i el nivell de ^{137}Cs; Tephra/P: profunditat de les capes de cendres i partícules més representatives, transformada al seu valor equivalent en aigua (densitat acumulada x longitud del core; la longitud del core correspon a la profunditat del sondeig amb correccions menors introduïdes durant el treball de camp); ^{137}Cs: profunditat del nivell d'acumulació de ^{137}Cs transformada al seu valor equivalent en aigua; Act. ^{137}Cs: activitat total del ^{137}Cs corregida al moment de la diposició; Balance/y: balanç de massa específic anual mitjà per al periode 1965-1993, en cm equivalents en aigua per any.

dríguez and Llasat, 1993) to the Southwest of Johnsons Peak. This Southwest oriented slope does not receive direct solar radiation and, as a consequence, snowmelt is lower than in North and Northeast oriented slopes. Thus, overall accumulation in this area is high and so the ^{137}Cs accumulation layer was probably not reached in the 11 m deep Q and R perforations.

The cores N and O were drilled in an area of ice cracks. It might be that they were drilled in ancient cracks subsequently infilled by snow after 1965, and so the ^{137}Cs did not accumulate. Another hypothesis, valid for all the four cores, is that summer supraglacial streams might have completely eroded this layer locally, as might have also occurred with the tephra layers.

The position of the equilibrium line altitude (ELA) for 1993 can be easily deduced from the samples containing ^{137}Cs (Figs. 2 and 3). It varies from about 200 m a.s.l. in the Dorotea profile to 250 m a.s.l. in the Caleta Argentina area. This variation is probably caused by the slope orientations related to the NE dominant winds, which mean the snow is redistributed slightly. While it accumulates mainly on the Dorotea profile, it can also be drifted out of the Caleta Argentina area. In Johnsons snowdrift area, the ELA is located at 150 m a.s.l. Given the considerable amount of snow accumulation, this ELA is valid only for this location and cannot be extrapolated to other locations on the Livingston ice cap.

Previous studies carried out between 1969 and 1989 on the Shetland Islands located the ELA at altitudes ranging from 110 m a.s.l. to 150 m a.s.l. (Curl and Brink, 1974; Orheim and Govorukha, 1982; Ren, 1988; Ren et al., 1995; Bintaja, 1995). On Livingston Island, Orheim and Govorukha (1982) suggested an ELA of about 150 m a.s.l. at Rotch Dome (east of Livingston Island) for the period 1971-74. Studies of the snow distribution on Johnsons Glacier during the summer of 1992-93 located the ELA at about 235 m (Vilaplana and Pallàs, 1993). The data presented by Ximenis et al. (this volume) for the Dorotea profile during the period 1995-97 located the ELA at 250 m. Therefore, previous observations and recent ELA determinations seem to indicate a rising trend in the ELA from the beginning of the 1970s up to 1997.

As described earlier, in those ice cores in which ^{137}Cs was detected, it always appeared in association with the 1970 tephra layer. This might mean that an intense ablation episode throughout the area (at least below 330 m a.s.l.; see location of PB in figure 3) melted, at least, all the accumulated firn and ice between 1965 and 1970. Thus, tephra particles were able to reach the depth of the ^{137}Cs level. This ablation episode, corresponding to a stratigraphic discontinuity in the ice, could have happened synchronically to the 1970 tephra deposition or later.

Figure 6 shows the average annual specific mass balance between 1965 and 1993 for the locations sampled. These annual specific mass balances are not representative of the real evolution of the glacier because the intense ablation periods, or the periods of possibly great accumulation, cannot be discriminated. However these rough mass balances indicate a great accumulation gradient related to the increase with altitude. Bintanja (1995) reported the same finding in the Ecology glacier (King George Island).

Even though it is a rough approximation, the mean annual specific mass balance at the location PB (330 m a.s.l.) is of 22 cm w.e. The 1993-94 precipitation was about 70 cm w.e., calculated from the snow accumulation at this point at the beginning of the summer season. This means that the annual accumulation at the highest point of

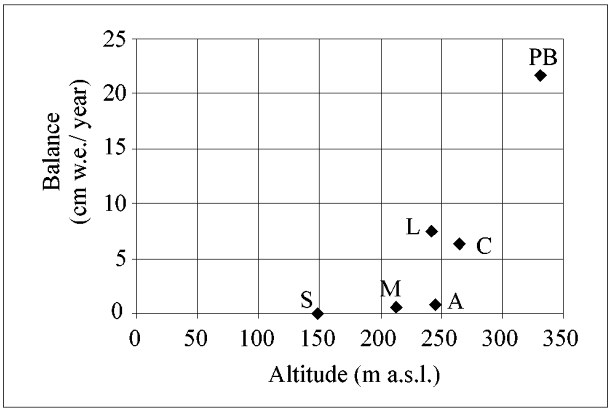

Figure 6: Mean annual specific mass balance in cm of water equivalent calculated from 1965 to 1993 for the locations where ^{137}Cs was found.

Figura 6: Balanç de massa específic anual mitjà, en cm equivalents d'aigua, calculat entre 1965 i 1993 per a les localitats on es va trobar ^{137}Cs.

Johnsons Glacier is approximately 1/3 of the precipitation. As reported earlier, according to Mitchell et al. (1990), the Antarctic shore area is very sensitive to climatic variations, and indeed all the observations presented here reinforce this hypothesis.

CONCLUSIONS

The stratigraphy of the cores, their cumulative density curves and the ice temperatures recorded confirm that Johnsons Glacier is a temperate glacier. It shows all the characteristics of a glacier which lacks seasonal accumulation cycles and which has an irregular but shallow densification pattern and summer ice temperatures near 0ºC (once the glacier recovers from the superficial cold winter wave).

The particle accumulations are not always concentrated in thin, well-defined layers. The layers vary greatly in thickness (3 mm to 2 cm) and there are also zonations of particles or else they are diffused along several decimetres of ice: Wind, solar radiation heating and water are assumed to be the main agents that control the vertical and horizontal redistribution of the particles.

In some ice cores the 1970 tephra layer is clear and readily identifiable. In others this is not the case and sometimes the tephra layer has been completely eroded. This demonstrates that snow drift areas and glacier structure (ice folds and cracks) cannot always be controlled completely, and that old supraglacial streams cannot be identified when choosing the drilling locations. Furthermore, it also means that the 1970 tephra layer does not always serve as a very good reference level.

Wind plays an important role in glacier evolution. The varying slope orientation of Johnsons Glacier relative to both the topographic obstacles, such as Johnsons Peak, and the prevailing NE wind gives rise to major differences in the accumulation of blowing snow (much greater on the Johnsons line). This implies significant variations in the equilibrium line altitude over the glacier.

The position of the equilibrium line in 1993, obtained from the ^{137}Cs spectrometry analysis, varies between about 200 m a.s.l. in the Dorotea profile and 250 m a.s.l. in the Caleta Argentina area. This variation probably depends on the slope orientation related to the NE dominant winds which cause the snow to be redistributed slightly. In Johnsons snowdrift area the equilibrium line, situated at 150 m a.s.l., has a local value. The most representative equilibrium line altitudes, at about 200 to 250 m a.s.l., show a rising trend from the beginning of the 1970s up to the present day.

When ^{137}Cs was detected, it always appeared in association with the 1970 tephra layer. This could signify an intense ablation episode throughout the area sampled (at least below 330 m a.s.l.; see location of PB in figure 3) which might have occurred synchronically to the 1970 tephra deposition or later. Specific mass balance estimates from 1965 to 1993 are rough mean values, not representative of the real evolution of the glacier, but representative of a general tendency. Equilibrium line altitudes and their variations must also be interpreted as indicating a general trend.

A rough estimate of specific mass balances for the different drilling points indicates a great accumulation gradient related to the increase with altitude. At the highest point of Johnsons Glacier the annual accumulation is approximately 1/3 of precipitation levels.

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