BANDING AND VOLCANIC ASH ON PATAGONIAN GLACIERS

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Abstract. On aerial photographs of the Patagonian ice fields several types of bands can be identified: (1) fine ogives similar to Lüder's lines in metals; (2) dirt bands which are both the outcrop of the annual debris strata of the *névé* and melt borders (the *Schmelzrände* of von Klebelsberg); (3) annual wave ogives below some ice falls; (4) annual ogives in regenerated glaciers, the formation of which is studied; (5) large melt borders which occur at longer intervals as a result of volcanic eruptions. These latter give evidence on the volcanic activity in the middle of the Patagonian ice fields.

Résumé. Sur les photos aériennes des champs de glace patagoniques on distingue plusieurs types de bandes: (1) ogives fines analogues aux lignes de Lüder dans les métaux; (2) bandes boueuses qui sont à la fois les traces des strates annuelles de débris du névé et des bordes de fonte (*Schmelzrände* de von Klebelsberg); (3) chevrons annuels (*wave ogives*) en dessous de certains chutes du glacier; (4) chevrons annuels dans les glaciers reconstitués, dont on étudie le processus de formation; (5) bords de fonte géants qui se forment à plus grands intervalles à la suite d'éruptions volcaniques. Ces deniers apportent des précisions sur l'activité volcanique au milieu des champs de glace patagoniques.

Introduction

This paper is chiefly based on the aerial photographs of Chilean Patagonia taken by the American Air Force in January 1946 (Trimetrogon Survey). Thanks are due to the Instituto Geográfico Militar of Chile, who allowed the writer to examine them.

This material has hardly been studied until now, and a careful examination of it gave the writer a great amount of information on the Patagonian ice fields, both the northern one (4400 km.^{2}) and the southern one (13,500 km.^{2}). These data are summarized in a book in Spanish on glaciology and Chilean glaciers[15]; in this the scores of unnamed glaciers which flow down from the ice fields are provisionally designated HPN 1, HPN 2, . . . for the northern ice field and HPS 1, HPS 2, . . . for the southern ice field. Examination of the moraines affords information on the flow of ice, while the trim lines show that several western glaciers have not receded during the past decades as much as those to the east.

Other information can also be obtained. Here we will only try (1) to throw some light on the confused problem of glacier banding, and (2) to elucidate a little the mystery of volcanic activity in the middle of the Patagonian ice fields.

Glacier Banding: Generalities

Glacier banding is important for the knowledge of glacier dynamics and structure; besides which, when the banding is annual, it gives the speed of the glacier at once. We must first render precise the still fluid terminology[1]. We shall call *bands* only *periodic* superficial markings of some breadth, not the outcrop of ice or dirt veins (Seligman's *infilled bands*). There are at least five different kinds of bands which we shall examine successively:

(1) On glaciers with an ice fall or a marked decrease in width a fine banding appears; these are the outcrops of layers of blue and bubbly ice and are of tectonic origin. Many names have been proposed for this, *shear plane ogives* (Seligman), *fine ogives* (Glen), *true ogives* (von Klebelsberg). Perhaps we can retain the old name of *blue bands* for them, if we call the infilled blue bands *blue veins* and the sedimentary ice bands *blue strata*.

(2) On a continuous glacier there are bands due to the annual sedimentary bands of dirt. These are Fisher's *Alaskan bands*, von Klebelsberg's *Schichtogiven*[2a]. The name ogives will not be used for these, as they often retain the festooned shape of the firn line.

(3) On a glacier with an ice fall, that is to say a steep, narrow channel where the upper part of the glacier breaks into seracs, the lower part remaining continuous and capable of transmitting pressure, annual *wave ogives* (*Forbes bands*, von Klebelsberg's *Sparren* or *chevrons*) develop.

(4) On a regenerated glacier, below the avalanche fan there is another type of annual ogives which Ives and King[3] also call Forbes bands, but which deserve a new name, as there are several differences; in particular the transverse waves are lacking.

(5) Long period borders of volcanic ash which are a typical feature of several Patagonian glaciers.

Fine Ogives and Plastic Layers

Numerous thin close blue bands are seen below several ice falls, for instance in the upper part of the Glaciar Rivera at the far end of the western fjord of Lago San Martin and also in the little glacier just east of the Glaciar Greve (far end of Fiordo Eyre) seen in the left foreground of Fig. 8 (p. 19). The layers of blue and bubbly ice are of similar breadth; they seem to be spoon-shaped and to emerge dipping 45° downwards, i.e. along planes of maximum shear, but this would be the shape taken by every transverse surface in the ice.

These bands are too numerous to be the outcrops of shear faults (*Scherrissen*) as stated by von Klebelsberg. They evince the periodic structure of the ice that von Klebelsberg calls *Blätterung*, and British authors *parallel banding* or *foliation*. Many glaciologists (Sharp[1] for instance) liken this structure to foliation in rocks, but it is well established that foliation in rocks is perpendicular to the maximum compressive strain, that is at about 45° to the maximum shear strain[4]. The "foliation" of ice, if it appeared along planes of maximum shear, would deserve a new name, the more so as there is no possibility of cleavage along it. These blue bands would be similar to Lüder's lines in metals, that is the outcrop of periodic layers approximately coincident with planes of principal shear stress in which most of the strain takes place[5]. We therefore propose to call this "parallel banding" of glacier ice *plastic layers* or *flow layers* as in metals.

Fig. 1 (p. 18) is a view of HPS 8, the next glacier to the east at the end of Fiordo Eyre (lat. 49° 01′ S. long. 73° 41′ W. in the preliminary chart). This glacier is divided into two juxtaposed streams by a medial moraine. On both streams two almost concentric stripes due (as we shall see below) to volcanic ash are visible, but on the eastern stream (right in the figure) the stripes are divided into many fine bands of irregular breadth. It seems likely that the melting of the plastic layers has carved furrows, and that the melt water and also rain water have carried ash into them, so that they have become superficial stripes of dirt outlining the outcrops of the plastic layers.

Sedimentary Bands and Melt Borders

In a continuous glacier, the debris which is deposited annually each summer on the *névé* makes dirt strata in the glacier which reappear undisturbed in the ablation zone, making sedimentary bands. The phenomenon is enhanced and sometimes entirely produced by the following mechanism. If a glacier has no crevasses near the firn line, and if in summer melt and rain water is abundant, dirt is carried forward on the annual strata of ice and on the glacier surface. When it finally emerges at the firn limit, the water evaporates leaving the dirt, just as a solvent leaves a greasy halo on cloth, or it may freeze with its dirt content. In either case, as the firn limit remains stationary for a long period at the firn line, a stripe ensues. These stripes are the *Schmelzrände* (melt borders) of von Klebelsberg[2b]. A pure melt border can be seen in the foreground of Fig. 8 at the boundary of a patch of bare ice caused by the overflow of small lakes on the crest, but in general it is quite impossible to distinguish between sedimentary bands and annual melt borders; all intermediate cases can be observed.

Water is in fact very abundant on Patagonian glaciers in summer; the C.A.B. expedition to the Monte San Valentin in December 1952 found a great morass between 1100 and 1150 m. (the firn line was at 1050 m.). In the Fitz-Roy district in January air temperature at the firn line varies on the average from 2° C. to 14° C. during the day and melting is uninterrupted, and so, as in Alaska, sedimentary bands are a very common feature.

The amount of summer rainfall which can sweep the debris cover from the ice determines whether these dirt bands vanish progressively as we go down glacier or not. If they do not, the debris stays on the glacier as ablation proceeds. If there is not too much, the individual particles dig holes into the ice and remain hardly visible when seen from the ground at any distance, narrow lines of dirt being seen at the outcrops of the dirt strata. When a certain number of strata accumulate, the cover gets thick enough to prevent ablation and we suddenly observe a covered glacier, limited at the top by a straight line. This is a common feature of the subtropical glaciers near Santiago.

The appearance is quite different when seen vertically from the air, as the pebbles in their holes remain visible. A few bands are visible near the firn line only if the dirt strata emerge at a large angle. They grow wider and wider and soon overlap. The appearance is then one of zones successively darker and darker as one goes down, and not of alternately light and dark bands.

An intermediate case with ablation of dirt equalling its deposition is given by a little glacier on the west side of Glaciar Grey at the southern limit of the Patagonian ice fields (Fig. 2, p. 18). A case of sedimentary bands rapidly overlapping between the firn line and the covered glacier is seen in Fig. 3 (p. 18). This is a vertical view of a tributary of the Glaciar Circo, on the north side of Monte San Valentin, at lat. 46° 33′ S. long. 73° 21′ W. Several large bands appear below a steep slope which cracks the glacier, but without disturbing its texture. Strata should exist above the slope, as a light, enlarged stratum is noticeable on the slope itself. At the foot of the slope, the speed of the glacier decreases owing to strong ablation, so the velocity of ice in the upper layers is strongly upwards and its horizontal component is smaller than at the bottom. This gives a kind of rotation of the strata, as drawn in Fig. 4 (p. 23). (This phenomenon, which is not the same as the old theory of "obstructed extrusion flow", has been observed in the field by McCall[6].)

WAVE OGIVES

As suggested by Ward, we give this name to the annual Forbes bands as seen on the Mer de Glace, Arolla or Trift Glaciers. They appear where there is an ice fall a little below the firn line and in Patagonia specially on the eastern sides of ice fields, where the difference between summer and winter is greater. Fig. 5 (p. 19) shows beautiful wave ogives on the northern slope of the Gorra Blanca (lat. 49° 05′ S. long. 73° 08′ W.), which follow a regular net of transverse crevasses, each ogive enclosing 4 or 5 crevasses. In the middle the ogives are 80 m. apart, so the glacier speed is there 80 m./year. A photograph which was not in the present writer's possession when he wrote a paper on glaciers near Monte Fitz-Roy[7], shows very light wave ogives on the Glaciar Grande, about 200 m. apart. Thus its speed is 200 m./year, which is less than stated by Dr. Guth, but is still a considerable speed for a glacier of alpine type.

In order to explain wave ogives, we know two facts which occur simultaneously below an ice fall: (1) the Reconstitution of the upper layers of the glacier encloses more air in winter than in summer, so the ice has alternately high and low bubble content. This was Collins's opinion in 1846, recently revived for instance by Fisher[8]. (2) The glacier slips over its bed more easily in summer than in winter, melt water acting as a lubricant. Consequently pressure waves arise at the foot of the fall and weaken progressively down glacier. This was Forbes's hypothesis, adopted also by Streiff-Becker[9] and proved by Haefeli[10]. We cannot explain by these two facts alone why the bands often become more visible when going down the glacier (see Fig. 5). So we must suppose that dirt gathers slowly in the depressions that correspond to the blue summer ice although this hypothesis still needs to be checked. It is also possible that the blue summer ice has a higher dirt content. A third hypothesis is that the fluctuations in the speed of the glacier make shear cracks, which pick up debris from the bottom. Both the second and third hypotheses agree with Leighton's observation that Forbes bands extend inwards, and are not merely a superficial feature[11].

ANNUAL OGIVES IN A REGENERATED GLACIER

Ogives which are similar to Forbes's wave ogives, but without their characteristic waves, can appear on a regenerated glacier fed by avalanches. Ives and King have studied them on a regenerated glacier in Iceland[3]. These were annual ogives extending into the glacier as layers of dirty ice. These layers were always bounded at the top, and in some cases also at the bottom, by shear surfaces with a considerable amount of debris.

In January 1956 the writer visited the regenerated glacier of the Paine Oesta, at the southern border of the Patagonian icefields. About 15 stripes of dirt and pebbles are visible on it between the avalanche fan and the snout (Fig. 6, p. 18). They are 100 m. apart and vanish progressively at the same time that radial cracks and blue bands multiply. Near the snout only a yellow hue in the ice remains. Its direction coincides with that of the fine blue bands, which are numerous and spoon-shaped (a few are visible in the left hand corner of the figure).

Although the writer was unable to dig near the avalanche fans owing to uninterrupted avalanches, he is convinced that these bands are largely only a superficial feature, a kind of melt border, forming in the following way. The avalanches are promoted by the fall of seracs, but in summer when these arrive on the fans they are chiefly composed of granular snow soaked with water. In these avalanches during spring and summer all the debris gathers at the periphery, the larger avalanches sweeping down all the debris left by the smaller ones. Thus each summer a belt of debris is formed at the foot of the avalanche fan. It is unnecessary for all the avalanches to contain debris, the important point is that most of the winter avalanches are of powder snow and the summer ones of granular wet snow.

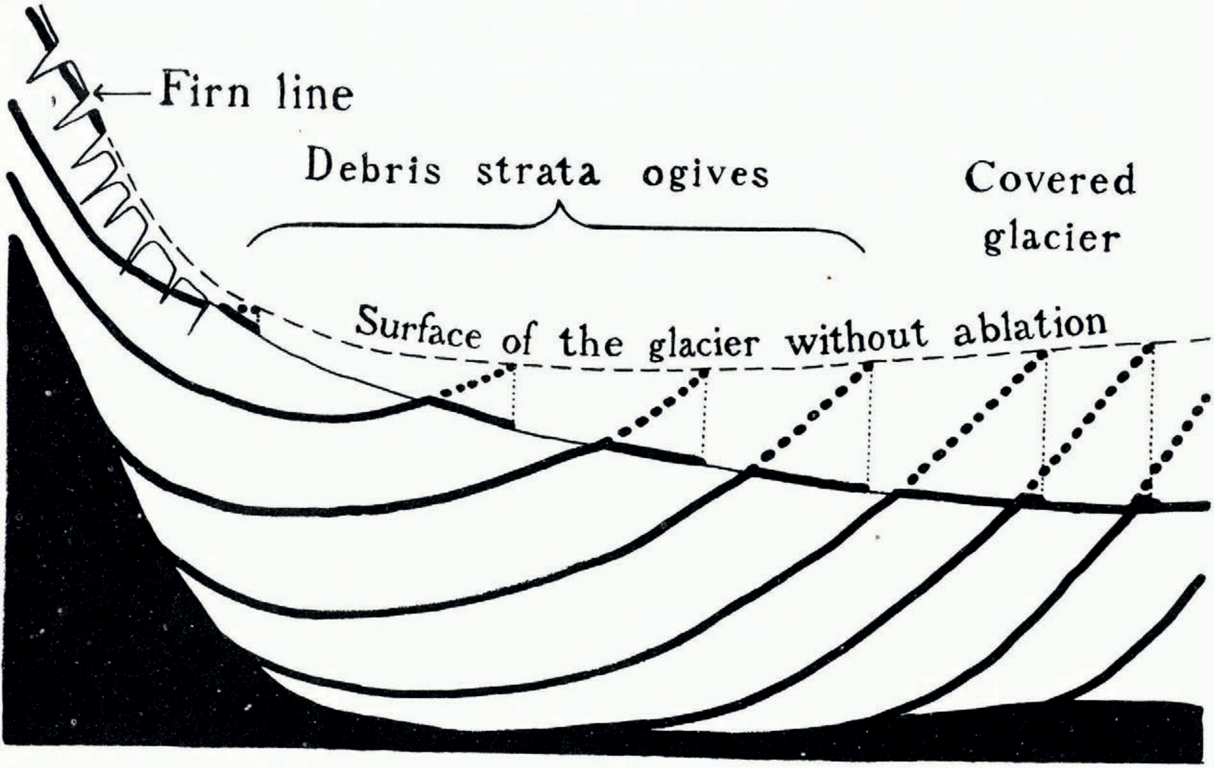

Fig. 4. Schematic longitudinal section of the glacier in Fig. 3, p. 17

The avalanche fans act as the accumulation zone of the regenerated glacier; their feet as the firn line. Thus the sedimentary bands in the regenerated glacier coincide with these annual belts of debris, just as they coincide with the melt borders on a continuous glacier. These sedimentary dirt layers will probably act next as plastic layers, or as shear surfaces, but it seems impossible in this case that any debris picked up from the rock bed can emerge near the avalanche fans; the horizontal velocity of the ice (100 m./year in the middle) is too great as compared with the vertical velocity (that is the rate of ablation of the ice—a few metres per year).

Large Melt Borders of Volcanic Ash

For a long time geologists were puzzled by the fact that volcanoes, so frequent along the Andes, disappear south of Monte Macá (lat. 45° 06′ S.), with the sole exception of Volcan Burney (lat. 52° 20′ S.). (We do not here speak of the dead craters in the middle of the Pampa.) Quensel in 1911 and Sapper in 1927 gathered random proof of some volcanic activity in the southern Patagonian Cordillera[12]. Padre De Agostini confirmed these suspicions[13]. In 1935 he picked up volcanic ash on Glaciar Chico. He writes also that:

> The inhabitants of the *estancias* near Lagos Cardiel and San Martin assert that they have several times seen a column of smoke arising from inside the Cordillera, east of the southern fjord of Lago San Martin, sometimes accompanied by noises and reddish flashes of flames which were visible by night, and by a fall of tenuous grey ashes.

Since then Salmi and Väinö Auer[12] found layers of volcanic ash in all the peat bogs of Patagonia and Tierra del Fuego which could not have been produced by the Volcan Burney alone.

On the 1946 aerial photographs can be seen: (1) a volcanic centre in the middle of the Glaciar Viedma at lat. 49° 24′ S. long. 73° 20′ W.; (2) large melt borders on many glaciers, undoubtedly composed of volcanic ash.

The volcanic centre of Glaciar Viedma, over which the writer flew in February 1952 (Fig. 7, p. 18), is very similar to the well known Grímsvötn in Iceland after an eruption[14]. Its area is about 5×2 km.^{2}, and it lies near the firn line at a height of about 1300 m. On the north and south-west sides volcanic rocks emerge above the glacier surface. The northern ones are already eroded by several little corries. In 1946 four ice tongues, two from the east and two from the west, flowed down into the crater, where several little lakes were seen, the greatest of 1 km.^{2}. All the eastern side of the glacier had crumbled into seracs, perhaps because it had once floated on a now emptied lake, perhaps because the ice has melted in contact with the ground as a result of volcanic heat.

Three melt borders of volcanic ash surround the crater and join the medial moraine issuing from it. Three melt borders can also be counted on the glacier, the upper one at the firn line, both in 1946 and 1952. It is tempting to attribute these three melt borders to three eruptions, happening at regular periods as in the Grímsvötn case. The period here would be about six years, and so a new one is anticipated in 1957–58.

Three large melt borders, the upper one nicely under the firn limit, were also visible in February 1946 on all the western glaciers between Glaciar Pio XI (lat. 49° 10′ S.) and Glaciar Jorge Montt (lat. 48° 20′ S.) (Fig. 8, p. 19), and on all the eastern glaciers between lat. 49° 10′ S. and lat. 48° 50′ S. They cannot be annual, as in the middle of the larger glaciers they are about 10 km. apart, whereas the annual speed cannot exceed 2 km./year.

As the wind always blows from the west in Patagonia (a south wind is very exceptional, and cannot have blown during each eruption), these ashes cannot be from the Viedma crater. There is no crater visible on the aerial photographs, either in the middle of the ice field or more to the west, so we must suppose the existence of at least one volcanic centre, covered by snow, in the middle of the ice field. Its eruptions should explain not only the three melt borders, but also the large flat valleys without vegetation where Glaciar Greve and HPS 7 end. There is evidence of sudden catastrophic overflows which no visible ice-dammed lake can explain. This hypothetic eruptive centre is placed at the north-west of Cerro Lautaro (3380 m., erroneously called Cerro Pirámide in the Carta Preliminar) at about lat. 48° 50′ S. long. 73° 40′ W. There may also be another, the one seen by the *estancieros* of Lagos Cardiel and San Martin, near Cerro Pirámide (∼2800 m., the most southern summit of Cordón GAEA; these names, given by De Agostini, Reichert and the numerous Argentine expeditions to this region, do not figure on any official maps). This should be at about lat. 49° 07′ S. long. 73° 15′ W.

A little cone, possibly volcanic, with a melt border, can also be seen at lat. 47° 09′ S. long. 73° 52′ W.

A periodical aerial survey of these regions would be of great interest. It is desirable that this should be included in the programme of the International Geophysical Year.

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ABLATION POLYGONS ON SNOW—FURTHER OBSERVATIONS AND THEORIES

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ABSTRACT. A general description of ablation polygons is given and variations from widely distributed regions are examined. After discussion of the conditions in which they most frequently develop, possible explanations are considered, leading to the conclusion that the polygons result from ablation by turbulence in the surrounding air, and that the dirt fringes to the polygons may be explained by the "normal trajectory" theory.

ZUSAMMENFASSUNG. Es wird eine allgemeine Beschreibung von Ablations-Polygonen gegeben, und Veränderungen nach weithin verbreiteten Regionen werden untersucht. Nach Besprechung der Bedingungen unter welchen sie sich am häufigsten entwickeln, werden mögliche Erklärungen erwogen, die zu der Schlussfolgerung führen, dass die Polygone das Resultat von Ablation, hervorgerufen durch Wirbel in der umgebenden Luft, sind, und dass die schmutzigen Ränder der Polygone durch die „normale Trajektorie" Theorie erklärt werden können.

INTRODUCTION

Attention was drawn to the phenomenon of "dirt polygons" in an article[1] in *Weather* by one of the present authors, and the correspondence resulting from this publication has been sufficient to justify a re-statement of the problem. Among the matters needing review is nomenclature, for the term "dirt polygon" is too suggestive of "soil polygon" and "stone polygon"[2,3], which seem to be quite unrelated in all respects other than shape. The phenomenon here described is essentially a feature of the snow surface, and the dirt fringe is so incidental that sometimes it does not even exist. In view of this confusion the revised terminology of "ablation polygon on snow" will be used in place of "dirt polygon".

Ablation polygons may be seen on the surface of partially ablated snowbeds. They consist of an array of shallow depressions in the snow surface, the centres of which are several inches apart. The cusp lines between adjacent depressions are generally, although not always, marked by a concentration of dirt: these lines form a polygonal pattern and will be called "dirt fringes" in this paper.

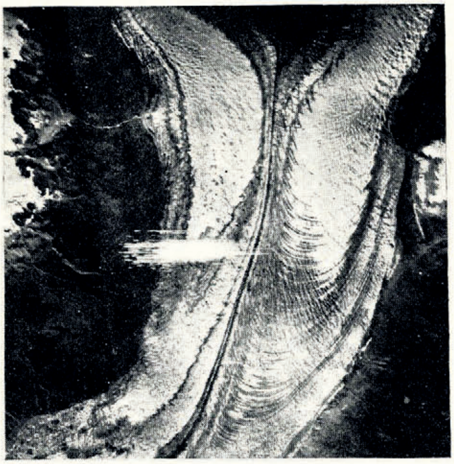

Fig. 1. HPS 8 Glacier, with two volcanic melt borders in each stream. In the eastern stream (right) the melt borders are dissected into stripes parallel to the plastic layers

Fig. 3. A tributary of Glaciar Circo with sedimentary bands

Fig. 2. Sedimentary bands which are also melt borders on a glacier near Glaciar Grey

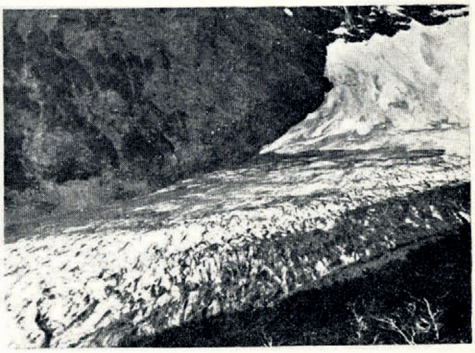

Fig. 6 (above). Dirt bands on a regenerated glacier of Cerro Paine Oeste

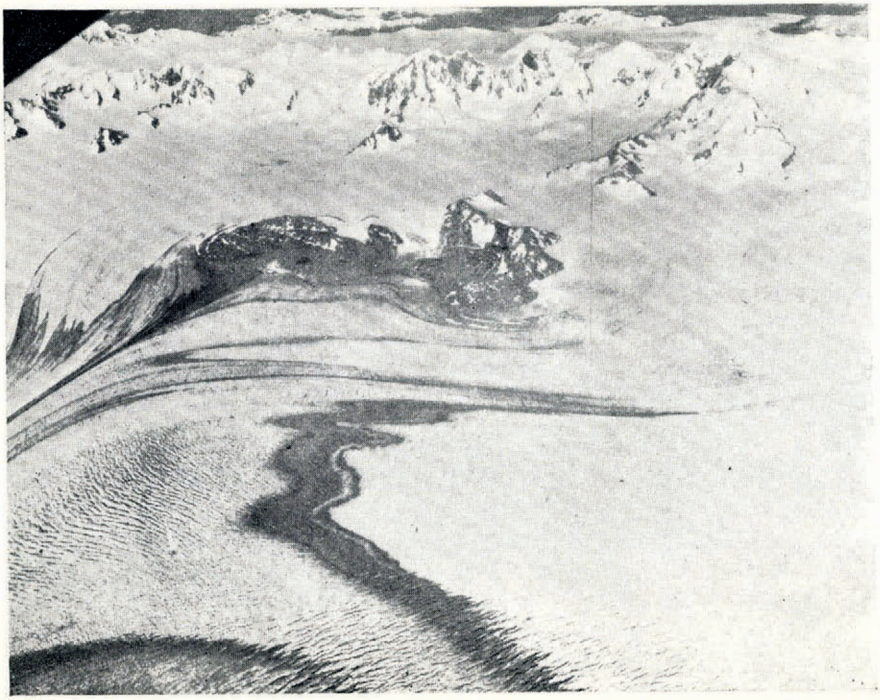

Fig. 7 (left). The crater in the middle of Glacier Viedma. In the foreground melt borders of ash. Behind, the Mariano Moreno range

Fig. 5 (page 19, top). Wave ogives on the northern slopes of Cerro Gorra Blanca. In the foreground, melt borders of volcanic ash on Glaciar Chico

Fig. 8 (page 19, bottom). Volcanic melt borders on the Glaciar Greve and HPS 7 (background). In the left foreground, fine ice ogives. Note also in the foreground a melt border around a patch of bare ice