Geogr. Fis. Dinam. Quat.
20 (1997), 315-320, 5 figg.

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ICE STRUCTURE AND DYNAMICS OF THE JUMEAUX GLACIER, VALTOURNANCHE, AOSTA VALLEY, ITALY

ABSTRACT: MOTTA L. & MOTTA M., *Ice structure and dynamics of the Jumeaux Glacier (Valtournanche, Aosta Valley, Italy)*. (IT ISSN 0391-9838, 1997).

This paper describes the type of ice and the dynamics of the Jumeaux Glacier, a conical glacier entirely situated below the snowline and supplied by avalanches. Examination of its structure from the rocky substrate to the surface thanks to the presence of an accessible subterranean stream net has shown that it is mainly composed of firn nearly transformed into infiltration ice with interbeddings of conglomeratic ice derived from the collapse of seracs forming at the tip of the cone. Cave ice and infiltration ice fillings are also present in gaping tension fractures, as well as debris-containing ice underlying compressive structures similar to overthrusts that are a feature of the lower half of the glacier. The presence of recrystallization ice, crevasses and overthrust structures shows that this is a true glacier, despite its tiny extent, while the distribution of the recrystallization ice and direct observation indicate that the ice layers in the abrasion zone move like thin sheets sliding over each other: the inner structure is thus totally different from that of corrie glaciers, and displays similarities to that of some tongues of regenerated ice in the large Alpine glaciers. A computerised avalanche dynamics model elaborated from the parameter values derived from direct observation of landslide debris was used to examine the glacier's supply processes. The conclusion is drawn that the main avalanches come to a stop below the glacier and only leave debris at irregularities in the terrain, such as bergschrunds, crevasses and terminal moraines, whose frequency and distribution are thus decisive. The glacier, therefore, is also very different from corrie glaciers in its replenishment pattern, since it lacks a true supply zone.

KEY WORDS: Glacial dynamics, Ice structure, Western Alps.

RIASSUNTO: MOTTA L. & MOTTA M., *Struttura del ghiaccio e dinamica del Ghiacciaio degli Jumeaux (Valtournanche, Valle d'Aosta)*. (IT ISSN 0391-9838, 1997).

Il lavoro descrive tipi di ghiaccio e processi dinamici del Ghiacciaio degli Jumeaux, ghiacciaio a cono situato interamente sotto il limite climatico delle nevi persistenti e alimentato da valanghe. Grazie alla presenza di un reticolo ipogeo accessibile, si è potuto analizzare la struttura del ghiaccio dal substrato roccioso alla superficie. Si è così appurato che il ghiacciaio è in larga misura costituito da firn molto prossimo alla trasformazione in *infiltration ice*, con intercalazioni di ghiaccio conglomeratico derivante dal crollo dei seracchi che si formano all'apice del cono del ghiacciaio. Sono presenti inoltre riempimenti di *cave ice* e *infiltration ice* in fratture tensionali beanti, e *débris-containing ice* a letto di strutture compressive assimilabili a sovrascorrimenti, caratteristiche della metà inferiore del ghiacciaio. La presenza di ghiaccio di rigelo per attrito, crepacci e strutture di sovrascorrimento dimostra che siamo in presenza di un ghiacciaio vero e proprio, nonostante la ridottissima estensione, mentre la distribuzione del ghiaccio di rigelo per attrito e l'osservazione diretta indicano che gli strati di ghiaccio nella zona d'ablazione si muovono come sottili falde che scorrono l'una sull'altra: la struttura interna è quindi totalmente differente dai ghiacciai di circo, e mostra affinità con quella di alcune lingue di ghiaccio rigenerato di grandi ghiacciai alpini. Per studiare i processi di alimentazione si è applicato un modello computerizzato di dinamica valanghiva, i cui parametri sono stati introdotti in funzione delle caratteristiche degli accumuli osservati direttamente. Si è concluso che le principali valanghe si arrestano più in basso del ghiacciaio, lasciandovi accumuli solo in corrispondenza a irregolarità del terreno quali crepacce terminali, crepacci e morene frontali, la cui frequenza e distribuzione risulta perciò determinante. Anche nell'alimentazione, quindi, il ghiacciaio si discosta molto da quelli di circo, essendo privo di una vera e propria zona di alimentazione.

TERMINI CHIAVE: Dinamica glaciale, Struttura del ghiaccio, Alpi Occidentali.

INTRODUCTION

The Jumeaux Glacier is one of the few ice bodies situated entirely below the local climatic snowline. It lies, in fact, between 2630 and 2873 metres a.s.l., whereas the snowline of its host mountain, Les Grandes Murailles, is at about 3100 a.s.l. The continued existence of this glacier is due to a morphological setting that is particularly favourable for the accumulation and preservation of avalanche ice, as shown by its cone shape (Nangeroni, 1927). Its snout is at the outlet of the gully conveying the avalanches that break off from Les Grandes Murailles between the Becca di Guin and Les Jumeaux (fig. 4). The glacier stretches over a step corresponding to the easily erodable mylonites interposed between the ophiolite unit of the Combin and the nappe of the Dent Blanche. The rim of this step is bordered downhill by small terminal moraines, below which

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The contents of this paper are the combined work of the two authors, performed mainly by L. Motta for the sections 1 & 3, by M. Motta for the sections 4 & 5. The figures, except fig. 2, are by M. Motta.

there are steep grass and debris slopes furrowed by a gully. Avalanches usually fall beyond the extremity of the glacier and stop at the mouth of this gully, which is the continuation of the supply gully. In 1923, 1935 and 1955, avalanches slid uphill across the valley floor and reached the Valtournanche provincial highway (Vanni, 1966a).

Its closeness to the valley floor has meant that the glacier has been studied by the Italian Glaciological Committee (CGI) since 1925. Indeed, it is one of the most assiduously monitored glaciers of this size in the Alps (L. & M. Motta, 1993a). It also lies within the area covered by the avalanche investigation campaign conducted by Vanni, then the Committee's secretary and glaciological operator in the Valtournanche, during the 1950s. His work has been followed by Giorcelli's measurements of changes in the glacier's front (1980-83), and the studies undertaken by the present authors since 1984. In 1993, the glacier survived the rapid reduction that extinguished many others in the adjacent Petites Murailles almost unharmed (L. & M. Motta, 1994), while in 1994 it even overrode the terminal moraine left after the last advance in 1984-85 (L. & M. Motta, 1995a).

Comparison of its snout fluctuations with those of other Grandes Murailles glaciers (L. & M. Motta, 1993a) has shown that they are not so much influenced by changes in the climate as by the metamorphism of the snow mantle and hence the frequency and features of the avalanches that feed the glacier. Vanni's observations (Vanni, 1966a) of those that slide down the main gully, known collectively as the «Jumeaux avalanche»[1], indicate that the importance of the NW wind is equal to if not greater than the size of the snowfalls. Moreover, as already stated, avalanches do not generally stop on the glacier, but may even erode it (L. & M. Motta, 1993a).

It is hardly surprising, therefore, that the glacier has changed little in the last 100 years. When there are heavy avalanches, it remains covered with residual snow throughout the year and advances, though the progress of its main tongue along the gully is hindered by their greater erosive action, since both their high energy (powder avalanches) and their high debris content enable them to sweep away all the snow cover along the gully, resulting in the early exposure of the ablation ice, and sometimes erode the surface layers of the packed snow, leaving the deep ruts clearly visible on many photos in the Committee's archives. When there are few avalanches, on the other hand, the glacier retreats. It occupies a smaller space and its surface is irregular. The avalanches no longer erode its snout and also tend more frequently to stop in its channel. Its lateral extension, therefore, has varied considerably in this century, but its front has remained in virtually the same position. It can thus be regarded as in a quasi-stationary state *sensu* Kotlyakov & Smolyarova, 1990. The moraines, too, respond to this particular dynamics. In periods of greater retreat, a series of small terminal moraines is laid down in the area between the lateral moraines of the Little Ice Age and the front (Nangeroni, 1927; L. & M. Motta, 1993a). In the advance periods, the glacier occupies the whole of the channel between the historical lateral moraines and destroys these little terminal moraines. They cannot form across the section of the gully below the glacier because it is too steep.

THE STRUCTURE OF THE GLACIER

In 1990, the glacier was well free of residual snow. Its bottom half displayed 14 bands of darker ice with englacial debris separated from each other by almost debris-free ice and parallel to the front, vaguely reminiscent of the ogives of larger glaciers. In 1994, on the orographic left of the front here were gently sloping shear surfaces along the bands of darker ice where the more surficial ice was sliding over the deeper ice, resulting in an overlapping, embricated structure. The slices at the front were particularly evident. They were curved upwards and overriding the approx. 1.5 high terminal moraine deposited in 1984-85 (fig. 1). The ice along the fractures separating the slices was lepidoblastic and full of shattered rock, whereas the slices themselves were granoblastic with little debris.

When the front was measured in September 1995 during the glaciological campaign, we found a series of channels on the orographic right near the front. These could be entered at little objective risk and we were thus able to examine the structure of the entire thickness of the glacier. The ice body was composed of imbricated slices resting directly on a rock and debris bed. They were separated by gaping fractures mostly obstructed by ice rich in rock fragments. Meltwater was flowing at the ice-rock boundary, though the many fractures meant that the hypoglacial streams were entirely in vadose conditions. Ice samples were taken for gross inspection and measurement of their density.

The body of the imbricated slices was formed of glassy transparent ice chock-full of subspherical air inclusions, usually less than 1 mm in diameter. These are arranged in parallel festoons with a bedding attitude less inclined than the slope (direction subparallel to the contours, dipping downhill). No boundaries could be detected between the crystals, neither by eye, nor by staining nor exposure to the sun. There were no visible inclusions of debris and its weight was less than 0.1%. Occasional millimetric veins of glassy, transparent but air-free ice were arranged parallel to the air festoons alongside them. The mean density for ten samples of ice with colourless veins was 760 +/- 20 kg/m^3.

There was a millimetric crust of opalescent, radiate-fibrous ice on the walls of the glacial channels. This was locally thickened in shapes like those of karst pseudostalactites. It covered a scallop-type erosive micromorphology.

The filling of the gaping fractures displayed a complex structure that varied from one point to the next. In the ca-

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[1] Vanni erroneously says that the Jumeaux glacier is at the base of a secondary gully that is also traversed by avalanches. He does, however, explicitly state that the Jumeaux avalanche forms «on the ridges between the Becca di Guin and Les Jumeaux», slopes that discharge into the glacier's supply gully.

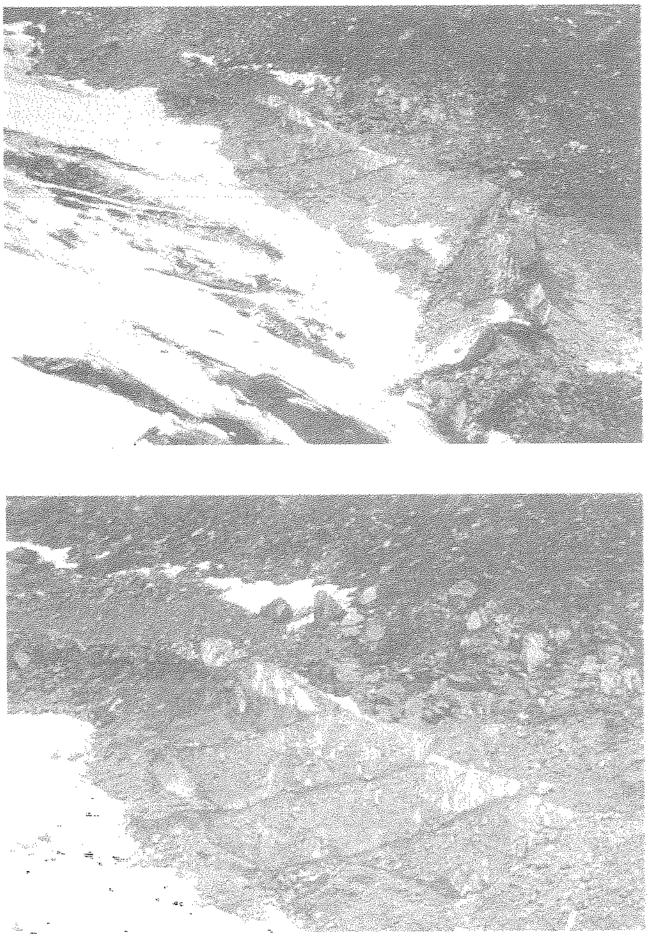

FIG. 1 - Front of the Jumeaux Glacier in 1994. Above: the orographic left sector showing the layers that make up the glacier: the bottom layer (right) is overriden by a 50-80 cm nappe on the terminal moraine. On the left, partly masked by the snow, there are shear structures similar to crevasses, though their shear plane is at a low angle and counter to the slope, separating one layer from the next. Below: magnified detail of the overthrust layers. The ice at the boundaries is darker because of its heavier charge of broken rock and also because it is mylonite ice (recrystallisation ice). Unpublished photos by M. Motta.

vity illustrated in fig. 2, a body of opaque, yellowish turbid ice (B) forms the ceiling of a subglacial cavity (A) covered with a crust of radiate-fibrous ice similar to that already mentioned. The yellowish body was formed of 4-5 mm diameter allotriomorphs and included intergranular air inclusions in a pendular setting (due to low water content, the air is present in continuous streams), and abundant, fine-grained rock fragments (about 5% in weight). The mean density for ice specimens was 800 +/– 10 kg/m^3. The surface displayed a rotted flow crust due to gradual reciprocal isolation of the ice crystals owing to the action of the air (destruction ice). Glassy, transparent ice (C) in the form of 5-25 mm diameter hyphidiomorphous crystals with no air inclusions is interposed between the yellowish turbid ice and the imbricated slices. This contains rock fragments, some large, packed together in lenses, with the result that the mean density is more than 1000 kg/m^3 (1110 kg/m^3 in one of the five specimens examined).

The characteristics of this ice indicate that the body of imbricated slices, with a density lower than 800 kg/m^3, is composed of firn of the type classed as an *névé d'infiltration* by Schoumsky (1957). Its structure shows that it is very close to transformation into infiltration ice, which displays autogenous growth inclusions arranged in bands (Schoumsky, 1957). The millimetric subvertical veins of transparent ice can be interpreted as distension fractures mended by exudation ice, especially cave ice. As to the filling of the gaping fracture, body B (fig. 2) displays the typical features of snow transformed into ice through the freezing of percolating meltwater (infiltration ice). Its high density, greater than that typical of firn shows that the transformation has been completed and that one can speak of true glacier ice. Layer C displays the features of debris-containing ice *sensu* Schoumsky (1957), formed by metamorphism through compression-melting in areas where there is a temporary excess of pressure. The most likely ex-

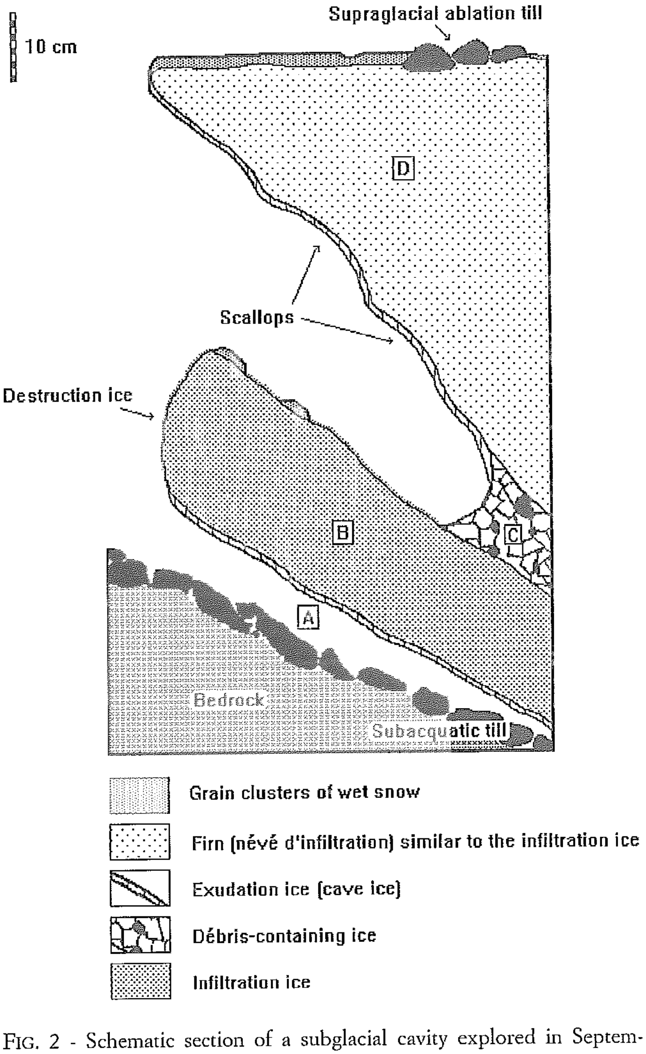

FIG. 2 - Schematic section of a subglacial cavity explored in September 1995.

planation of the B,C and D association is that snow accumulated in a crevasse which opened in body D, and was then changed to an ice-wedge that tilted downhill owing to the movement of the glacier to become body B. This has been partly subjected to the metamorphic effects of its partial overriding by the imbricated slice and has thus given rise to the ice in layer C.

The scallops morphology in a karst environment has recently been related to the dissolving action of damp air circulating in the passages (Badino, 1995). Its association with the cave ice crusts is a sign of the perhaps seasonal alternation of sublimation and melting-refreezing. At below-zero temperatures, there are no sheets of surface meltwater and there is a predominance of erosion by sublimation induced by the air circulating in the subglacial systems, whereas at higher temperatures melting-refreezing prevails. During our surveys, in fact, the air was being driven from the upper to the lower inlets of the subterranean system by the differences between the intraglacial and the outside temperature and between the levels of the inlets (Badino, 1995). In view of the modest nature of these factors in our case, the presence of a distinctly perceptible current of air indicates that the subterranean system has a very small impedance, or that it is composed of extensively communicating cavities devoid of narrows.

In October 1996, the observations were completed by the examination of a subterranean system at a higher altitude. Once again, the full thickness of the glacier was investigated (fig. 3). It was found that the body of imbricated slices was formed of ice similar to that shown in fig. 2, but with distinguishable crystals varying in diameter from 2 mm in the deeper to 1 mm in the surficial layers. Examination of undisturbed cores revealed the presence of closely packed foliations (in section 3 per cm) resembling those observed in the regenerated ice-flows of the Lys Glacier (L. & M. Motta, 1995b). The general structure of the imbricated slices was conferred by the overlapping of layers, often marked at the summit by moraine material. Near the surface, interposed between one layer and the next, there was a layer of columnar ice (Class 8ic of the ICSI classification of seasonal snow cover on the soil, Colbeck & *alii*, 1993), exclusive to the snow mantle and the ice derived from it. This proves beyond doubt that the ice capping it, and perhaps the whole of the rest of the slice, is derived from the transformation of snow, as is indeed confirmed by the density measurements (fig. 3), which are indicative of firn. According to Colbeck & *alii*, (1993), columnar ice comes from the refreezing of percolating water due to thermal conduction in the surrounding layers when these are particularly cold. The vertical channels through which percolation takes place form more easily when the snow is well stratified. This suggests that the original snow did not come by direct precipitation but from an avalanche, since avalanches generally display thick laminations caused by shearing (L. & M. Motta, 1993b).

A DYNAMIC SUPPLY MODEL

The culmination area of the Jumeaux Avalanche determines the supply of the glacier. This area was measured and the dynamic avalanche model of Leaf & Martinelli (1982) was used with the *Tebe* program devised by L.M. to determine the dynamic features of the avalanche in significant conditions. This model considers the glacier trunk only, even where there are no counterslopes at the front. At the sides, on the other hand, the successive terminal moraines form natural barriers, though these are filled by the first avalanches with the result that those which descend later are not impeded. Stratigraphic analysis of ava-

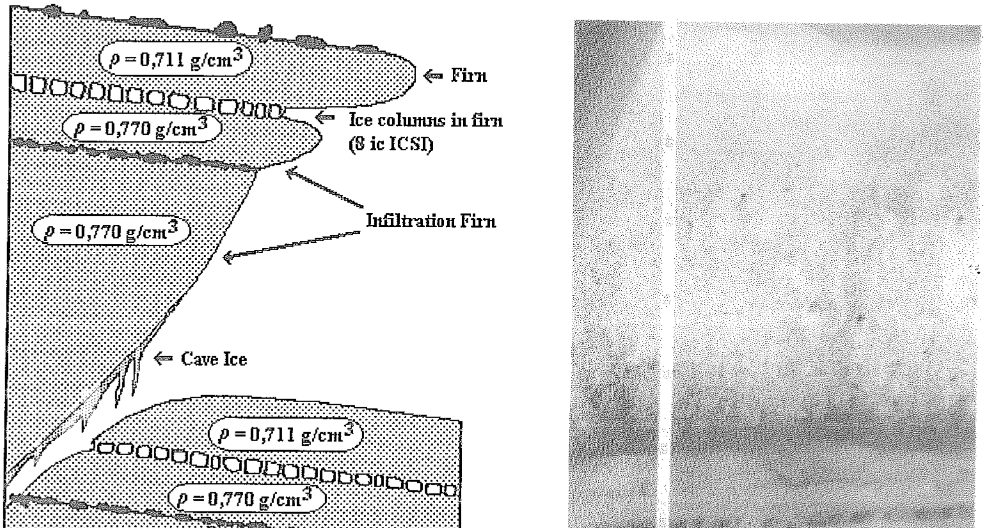

FIG. 3 - Left: stratigraphic section of the inlet of the subglacial system explored in October 1996 with englacial debris in black. Right: upper part of the section showing the columnar structure and distribution of the dirt bands.

lanche residues carried out in 1994 and 1995 showed that they were always derived from powder avalanches.

The results provided by the model (fig. 4) agree with those obtained by direct observation from 1984 to 1996 showing that:

- small avalanches from a snow mantle ranging from 10 cm in thickness (wet spring snow) to 15 cm (dry winter snow) go beyond the glacier front and stop at the mouth of the lower gully; avalanches of this type occur many times every year.
- avalanches from a mantle ranging from 10/15 to 30/40 cm thick occur every year and come to a stop on the valley floor;
- avalanches from thicker mantles sweep across the floor and may climb up to the road on the other side. As already mentioned, this happened three times in the period 1923-1966 (Vanni, 1966a).

The Jumeaux Avalanche, therefore, only leaves deposits on the surface of the glacier where there are irregularities in the terrain, and it is these that govern its supply. There are three kinds:

- bergschrunds: these are completely filled with snow by the end of the winter and probably give rise to the bulk of the ice-body. During recession periods, those at the apex of the glacier cone isolate small seracs (Motta, 1987), whose collapse originates layers of regenerated ice alternating with layers of avalanche snow;
- crevasses: here the snow is turned to ice by refreezing of the percolating meltwater:
- terminal moraines: the heaps of avalanche residues that form before these moraines protect the glacier front until late in the Summer and sometimes for the whole of the year.

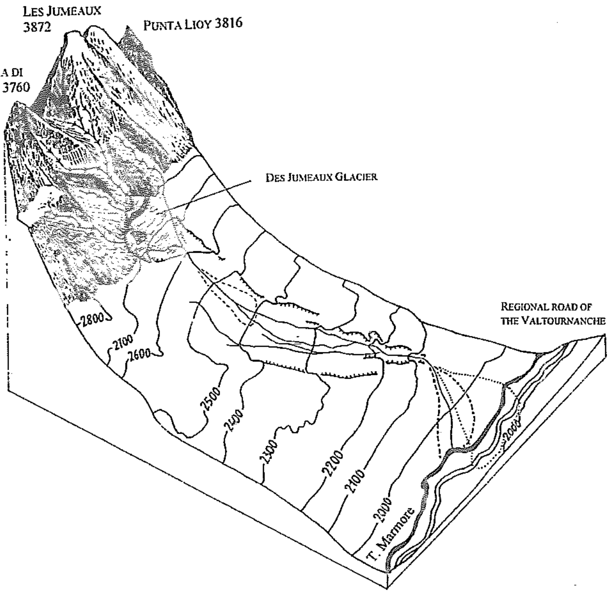

FIG. 4 - Halt positions of the «Jumeaux Avalanche» in function of different snow mantle thicknesses according to the Leaf & Martinelli model (1982). (See text, section 3).

GLACIAL DYNAMICS

Both the upper part and the front of the Jumeaux glacier are composed of firn that has nearly passed into infiltration ice (fig. 5a), evidently because the whole of the glacier lies at a low altitude and long daytime melting of its surface results in the widespread percolation of meltwater. The firn is derived from avalanche deposits on both the outside of the glacier and inside its crevasses. During recession years, «regenerated ice» makes a substantial contribution. This is the result of secondary recrystallisation, but has a conglomerate structure derived from the rehardening of seracs that topple from the outlet of the feeder gully (*glace détritique sensu* Schoumsky, 1957). One of these collapses witnessed in 1986 (Motta, 1987) covered much of the fractured ice zone of the front. Layers of firn and regenerated ice slide over the rock substrate with a viscous-plastic flow and become progressively thinner. Cracks imposed by the unevenness of the substrate form crevasses that collect avalanche snow that also changes to infiltration ice (fig. 5b) more quickly than on the surface, presumably because the lower temperature in a crevasse encourages refreezing of the meltwaters it has intercepted (fig. 5c). Movement of the glacier and filling of its crevasses with scree from Les Grandes Muraillles or rock waste brought down by avalanches result in a deep stack of debris-containing ice. Sliding of the upper over the friction-restrained lower layers begins to be perceptible in the middle of the glacier. Recrystallisation ice (ice mylonite) forms along the overthrust shear surfaces thus created mainly at the boundary between one layer and the next, but sometime within a single layer. The front is thus composed of sequences of overlaid «nappes» consisting of successions of debris-containing ice and firn with infiltration ice lenses, separated by recrystallisation ice. Near the front, the glacier is composed of imbricated slices sliding over each other. As already stated, they override the terminal moraines when the glacier advances, as in 1994 (L. & M. Motta, 1995a). These slices thus move the snout faster than surface ablation can dismantle them as they descend. Their speed can be judged from the fact that ablation of the nearby Lys Glacier at about the same altitude was 4.5-4.7 cm a day in 1994 (L. & M. Motta, 1995b).

CONCLUSIONS

Our observations suggest that the firn which accumulates in the upper part of the glacier takes 20-25 years to reach the front. The presence of infiltration-recrystallisation ice and recrystallisation ice, found only in a glacier because they are generated by dynamic processes associated with its flow (Schoumsky, 1957), and crevasses and overthrust structures shows that the ice body is certainly moving and is thus a true glacier, even though its tiny size (0.046 km^2) places it just outside the World Glacier Inventory (WGI) recording limit adopted in Italy (0.05 km^2, compared with the 0.01 km^2 used in Switzerland; Secchieri, 1985).

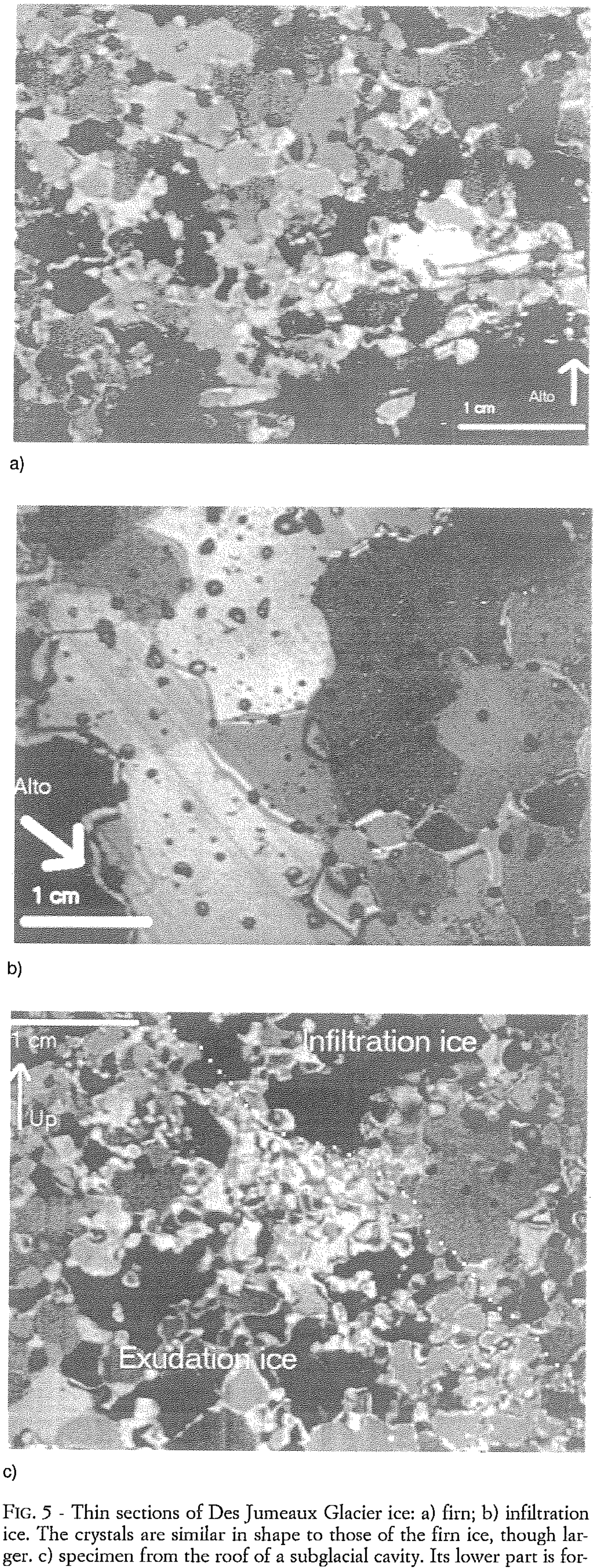

FIG. 5 - Thin sections of Des Jumeaux Glacier ice: a) firn; b) infiltration ice. The crystals are similar in shape to those of the firn ice, though larger. c) specimen from the roof of a subglacial cavity. Its lower part is formed of bubble-free exudation ice composed of small, very jagged crystals.

Examination of the surface cracks according to L. & M. Motta (1993b), the accumulation processes and the distribution of the various types of ice has given a model clearly different both from the conical pattern suggested by Vanni (1966b), who portrayed this glacier as a large avalanche fan, and a corrie glacier (see model from McCall, in Lliboutry, 1965 and Fairbridge, 1968). Since the Jumeaux is devoid of any special morphological features, its dynamics can probably be extended to other cone-shaped glaciers on the Alps, such as the Montasio (Julian Alps), the Talancia Girard (Great Lanzo Valley), the Viso (Varaita Valley), etc. These glaciers are classed as «mountain glaciers» by the WGI along with corrie glaciers, but would seem to be distinguishable on account of both their different geomorphological and climatic location due to their particular supply system, and their dynamics, which makes them more akin to the tongues of regenerated ice displayed by the large Alpine glaciers (Lys, Tza de Tzan and others) that often shift internally through the sliding of relatively thin superposed slices separated by sheets of recrystallisation ice.

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