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ROCK GLACIERS

Abstract

After an inventory of covered, uncovered glaciers and rock glaciers, of more than 12,000 km² of high cordillera and precordillera, and after an analysis of the world's literature, various types of rock glaciers in their active, inactive and fossil stages were determined. The high Andes, with its cold and dry climate, its diurnal intense incoming radiation and nocturnal outgoing radiation, with rocks' weathering into blocky materials, with abrupt topography as a consequence of deglaciation and also deglaciation conditions, are providing the ideal environment for the formation of rock glaciers.

Rock glaciers are polygenetic: as a consequence of deglaciation, and as a consequence of ideal conditions of accumulation of debris and snow.

There are rock glaciers which are moving very rapidly: "surging rock glaciers".

Rock glaciers are considered an "underground mountain glacial" facies of the dry cold geocryogenic regions which correspond to the "uncovered ice" facies of the areas with more snow precipitation.

A tentative distribution diagram on active and Quaternary rock glaciers along the Andes and southern hemisphere is presented.

The significance of rock glaciers from the hydrological and paleoclimatological view point is indicated.

Rock glaciers in their active stages are deformed talus cones and debris tongues, by motion of the lose debris of the surface layer or of frozen inner core, composed of massive or interstitial ice. The real rock glaciers are those formed from talus cones and from protalus ramparts: these are the primary rock glaciers.

Rock glaciers derived by melting of valley glaciers are called: debris covered glaciers or secondary rock glaciers. There are other types of rock glaciers: such as those produced by the covering of firn layers with debris, or by the overrunning of rock glaciers by glaciers. The high arid Andes, with rocks breacking up into blocky materials (basalts, andesites and porfirites), with clear skies favouring strong daily radiant input and nocturnal cooling and deglaciation conditions are providing ideal circumstances for the formation of rock glaciers. Rock glaciers are a Holocene (periglacial-glacial) process which reshaped the glaciated valleys after the retreat of the Pleistocene glaciation.

Several levels of rock glaciers, protalus ramparts, buried fossil soils are observed. All of these features are related to climatic oscillations which have occurred during the Eastern Central Andes' Holocene. Fossil rock glaciers are observed in this region at 1500—2000 m below the present active ones.

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INTRODUCTION

In geocryogenic mountains there are various processes producing rock glacier type features. The environmental conditions conducive to the formation of rock glaciers are not yet very well known. Most of the types of rock glaciers are formed within the domain of the geocryogenic or periglacial regions. Rock glaciers are produced by different processes:

(1) accumulation of debris and snow below avalanche chutes in mountain valleys in which the structure provides adequate spacing of avalanche chutes and rocky material. Here are included the tongues produced by the growth of the protalus ramparts (*Hangblockwulst* in German) which with further growth are changed into rock glaciers;

(2) accumulation of debris layers on top of firn at the end of autumn;

(3) by the motion of glaciers overriding rock glaciers;

(4) as the final stage in the vanishing of rich-in-debris valley glaciers;

(5) by the combined action of the above mentioned processes.

There are certain similarities between the active stages of the rock glaciers and solifluction (soligelifluction) lobes. There are four conditions which should be met by a rock glacier in order to be considered active: (1) it should incorporate ice masses or have sufficient interstitial ice, (2) it should move, (3) it should have a steep front, (4) it should be located at the foot of a mountain slope or in a valley floor or on a valley side. The gelifluction lobes are not fed by avalanche chutes nor do they display the typical long troughs on their surface; they also lack transversal arches. Furthermore gelifluction lobes should not contain a core of massive ice: since this mark is a feature of rock glaciers related to vanishing ice glaciers.

There are few reports on fossil rock glaciers (Czajka, 1955; Hövermann, 1972; Derbyshire, 1973). This lack is due to the following factors: (1) it is a new research field; (2) due to a better knowledge of the glacial process some rock glacier features were possibly missinterpreted as moraines; (3) the little information regarding the evolution of rock glaciers from the active to the fossil stage. In this respect it is to wonder if the features described as boulder fields, boulder slopes, stone rivers, are actually fossil stages of rock glaciers. In German literature, rock glacier (*Blockgletscher*) is a genetic feature of block streams (Czajka, written comm., 1975). About 100 items are the available bibliography on rock glaciers, which have been used for this review. The available Soviet Union references are very few, and the author will welcome from his colleagues the exchange of information in this field.

At this moment the Instituto Argentino de Nivología y Glaciología, of CONICET, is compilling an extensive inventory of glaciers of the Argentine high central Andes; information here presented is in part from this inventory. The author would like to thank Dr. Henri Bader, consultant of IANIGLA, for suggestions and information during the early stage of this work, and Mrs. Lydia Bengochea for data related to glacier and rock glacier inventory. This is a preliminary report, which as a first

approach seeks a morphologic understanding; it will be expanded and checked by further field surveys, experimental data and laboratory findings. Herewith, I also thank Mr. Robert BRUCE for his typing and pre-editorial help.

TERMINOLOGY

When SPENCER (1900) described a peculiar form of talus formed as a tongue at the foot of a glacial cirque, he relates what we today call a talus glacier or a rock glacier. The term *rock glacier* after its introduction by CAPPS (1910) is being widely used in the USA, Canada and England (IVES, 1940; WARHAFTIG and COX, 1959; OUTCALT and BENEDICT, 1965; MILLER and ANDERSON, 1968; POTTER, 1972; WHALLEY, 1974). KESSELY'S proposition (1941) to use *rock streams* instead of rock glacier was not followed. The word *Chrystocrenes* was proposed by TYRRELL (1919) to describe the motion produced in taluses by the freezing of spring waters. This term was subsequently not used. In Switzerland the term *coulées des blocs* was used as an equivalent of "rock glacier" (CHAIX, 1923—1943). In France the term *glacier rocheux* is used (CAILLEUX and TAYLOR, 1954; TRICART and CAILLEUX, 1967); they consider that rock glaciers are a glacial process and not a periglacial one. Also in France, LLIBOUTRY (1953, 1955, 1956, 1961 a—b) makes a differentiation between "glacier d'éboulis" of fine materials and "glacier rocheux" of coarser materials.

In Argentina (CATALANO, 1923) used the term *litoglaciares* (lithoglaciers), for moving detrital materials cemented by ice. He also proposed the term *glaciolitos* to describe the materials accumulated or produced by rock glacier action. He placed the lower limit of the Puna fossil rock glaciers at. 4000 m, and the active ones at 5000—5500 m. In Italian the words *pietrai semoventi* (moving stones) as well as contraction and compression moraines are used (CAPELLO, 1947—1960—1963).

The American Geological Institute's glossary (1972, p. 615—723) defines two terms: *rock glacier* and *talus glacier*. The first as: a mass of poorly sorted angular boulders and fine material cemented by interstitial ice a meter or so below the surface, occurring in high mountains in a permafrost area, and derived from a cirque wall or other steep cliff by frost action. It has the general appearance and slow movement of a small valley glacier... etc. (p. 615). The second as: a rock glacier consisting of loose debris on a steep slope (p. 723). In German the equivalent terms for rock glaciers are: *Blockgletscher* (CZAJKA, 1955; TROLL, 1944—1958) or *Erdgletscher* (HÖVERMANN, 1972; QUIRING, 1928); they are considered as a part of the stone rivers (Blockströme) (GRÖTZBACH, 1965, and CZAJKA, written comm., 1975).

When attempting to define conditions of ice-cored moraines and rock glaciers, ØSTREM proposed that rock glaciers should be moving frozen bodies with interstitial ice but not massive ice (ØSTREM, 1971; HUGHES, 1966). However the difficulty with this proposal lies in the fact that it is difficult to distinguish a debris covered glacier which is in the final stage of melting in its lower part rich in debris, from an ice-rich rock glacier. ØSTREM (1971) proposes also that: when material located in front of a glacier (frontal moraines) moves, than it should be considered a rock glacier; if it does not move then it should be called a moraine.

THE ACTIVE AND INACTIVE STAGES OF ROCK GLACIERS

The bulk of the information on rock glaciers is related to their active and inactive stages; i.e. rock glaciers that contain ice and are moving. Active rock glaciers are related to permafrost conditions or at least discontinous permafrost.

THE ENVIRONMENTAL CONDITIONS

The most important factors in rock glacier distribution are:

Climate

Since rock glaciers are located near the permafrost boundary, the mean annual temperature in which they are formed is below 1° or 2°C (CORTE, 1953—1955; LLIBOUTRY, 1956; WARHAFTIG and COX, 1959; POTTER, 1972). It has been indicated that mountain areas with cold continental climate, predominant clear skies and low snow precipitation are the ideal conditions for rock disintegration and rock glacier formation (THOMPSON, 1962).

Precipitation is mainly snow: LLIBOUTRY (1956) indicates that for the Chilean Andes, rock glaciers are atabout 1000 mm of yearly precipitation; POTTER (1972), places his ice-cored glaciers at 1200 mm precipitation. One of the most important aspects in the formation of rock glaciers is the snow accumulation. There is very little information regarding sublimation, evaporation, fusion and refreezing within the body of the rock glacier.

The effect of exposure and surges on the distribution of glaciers and rock glaciers

In the dry part of the Andes the effect of expcsure and radiation is of fundamental significance in the distribution of glaciers and rock glaciers and associated features. This can be observed at the same levels across some valleys; while rock glaciers are in the south facing side (cold side); on the oposite (warmer side) solifluction features prevail (Pl. 1). In a south-east facing slope, there is a glacier moving and cutting a rock glacier flowing from a warmer slope and even higher mountain. In other cases there are glaciers in the south facing slope and rock glaciers in the north and east facing slopes (Pl. 2). The effect of surges on rock glaciers are observed in the Plomo region. Here a surge dammed the Plomo River in 1934. This surging cuts rock glaciers leaving them without a supply of debris. It is to note in these figures that surging glaciers have taken material from former rock glaciers building lateral moraines. Also surging ice has scraped the loose debris from the rock glaciers surface and left it bare on the slope without a debris pattern (Pl. 2).

Rock types

It has been indicated that granites, basalts, quarzites, sandstones are proper rocks for building rock glaciers (WARHAFTIG and COX, 1959). In the central Andes, extensive areas of rock glaciers are of andesites and porfiry rocks; the presence of these types of rocks partly explains the formation of rock glaciers in this region.

Morphological conditions

According to my observations of rock glacier development, primary rock glaciers are formed on the steep faces of valleys left by glaciers (Pl. 3). The presence of these steep slopes are necessary.

Latitudinal and altitudinal zonation

When inventoring large areas of glaciers and rock glaciers as is occurring in the high Andes, two very well differentiated facies are observed: high up is the glacier (uncovered ice) facies and below, the rock glacier facies (Pl. 1, 2). In some cases a transition from glaciers to rock glaciers is seen (CAPPS, 1910, p. 371; WARHAFTIG and COX, 1959). For a given slope we always observe the glacier facies high up and the rock glacier facies lower down (Pl. 2). In very few cases glaciers have cut or "trimmed" rock glaciers (Pl. 2, up.), this according to my own observations, and of LLIBOUTRY (1956) in the Chilean Andes, and of WARHAFTIG and COX (1959) in Alaska.

The altitudinal belt, for active rock glaciers is 900 m in the Aconcagua region, and for the dry eastern Andes a higher elevation. According to the present information, the rock glaciers we are observing in the dry Andes, were not found in the cold humid environments (oceanic) of Scandinavia, Southern Patagonia and the western part of the Cascades (THOMPSON, 1962). The thickness of the altitudinal belt where rock glaciers exist should increase as we move from the cold humid zone to the dry cold one. This belt should dip in the cold humid zone.

Glaciers, ice-cored moraines and rock glaciers

The limit between glaciers and rock glaciers, as stated, is deeping towards the cold humid regions (BARSCH, 1971). This is observed in the Canadian Rocky Mountains (*op. cit.* p. 206) and in the central Andes at 30° lat. (CORTE, 1955). This is due to the fact that with an increase in precipitation there is an increase in the speed of ice flow, and consequently a removal of materials located in front of the ice. In the drier zones which receive more radiation and suffer more evaporation, the ice is covered with a debris layer which impedes ice melting. Since rock glaciers are a facies located below glaciers, the névé line is located above the rock glaciers. In the Swiss Alps, the active rock glaciers are normally located at no more than 400 m below the névé line; however this value is not equal for the rest of the world (BARSCH, 1971a).

Regarding the relations between glaciers, ice-cored moraines and rock glaciers (ØSTREM, 1965—1970—1971; BARSCH, 1971a), as indicated by WHALLEY (1974), the ice-cored moraines are part of a continuum from clean glaciers, through rock glaciers with ice cores, to stagnating masses of ice and ultimately to relict features devoid of ice content. Ice-cored moraines according to WHALLEY (*op. cit.* p. 50) would be a stage of this sequence being characteristic of small continental glaciers.

MORPHOLOGIC-GENETIC TYPES OF ROCK GLACIERS

According to some authors (LLIBOUTRY, 1953—1955—1956, 1961 a-b; CORTE, 1953; CORTE, *et al.*, 1957; IVES, 1940; WARHAFTIG and COX, 1959; OUTCALT and BENEDICT 1965; BARSCH, 1969, 1971 a-b; CAPPELLO, 1943—1947—1960—1963) and our own information from over 12,000 km^2 of glacier inventory in the high Andes, we can differentiate the following genetic types of rock glaciers:

(a) primary rock glaciers: "type P", subtypes: P1, P2, P3 and P4,

(b) debris covered glaciers or secondary rock glaciers: "type S", subtypes: S1 and S2,

(c) rock glaciers affected by the action of glaciers: "type RGGl", subtypes: RGGl 1 and RGGl 2,

(d) rock glaciers of mixed origin: "type RGMO",

(e) rock glaciers of rapid motion: "type RGRM".

Primary rock glaciers: *"type P"*

Under this category I have included the rock glaciers produced by: avalanche chutes, the covering of firn or névé layers and debris, the rapid accumulation and motion of the debris surface or the frozen core and by the growth of protalus ramparts.

Sub-type P1: this sub-type includes all deformed talus cones located below avalanche chutes which are providing snow and debris (Pl. 1). These rock glaciers are located in the south facing slopes of the valleys left by the glaciers. In their initial stages they start as a debris cone, avalanche cone, talus cone, etc. (DI COLBRETALDO, 1946); see the Am. Geol. Institute: talus glacier as a synonym of rock glacier (1972). In later stages of the debris motion, they are deformed and transformed to valley side rock glaciers (OUTCALT and BENEDICT, 1965).

Rock glaciers of this sub-type are presently being formed near the Aconcagua region in the Horcones Valley at 3500—3700 m and at 3700 to 4100 m in the drier eastern Andes (Pl. 1). This sub-type of rock glacier does not show thermokarst features on the surface; indicating the lack of massive ice below the detrital cover.

There is little information on this sub-type of rock glacier; it is presumed that the ice is interstitial; however the sections presented by DI COLBERTALDO (1946) indicate the layers of ice and debris below avalanche chutes. It is presumed that the lack of elaborate arches of the superficial material is due to the low rate of motion of loose cover.

Sub-type P2: this sub-type of rock glacier was described for the Andes by LLIBOUTRY (1961 a). They are produced by covering of firn debris, layer after layer, until they become sufficiently thick to flow. LLIBOUTRY proposes to designate this type of rock glacier as "glaciers enterrés" or buried glaciers. They are indicated for the 4000 m. Such rock glaciers should be considered related to the initiation of glaciers or glaciation as "nivation niches".

Sub-type P3: under this sub-type, I would like to propose to include the rock glaciers which show a strong deformation of the talus bands. As previously stated the bands in this sub-type of rock glacier are bent down to the terminus of the rock glacier. Since this happens in the vicinity of true glaciers, and since this is the leeward side of the snow fall, it is to be presumed that in this type of rock glacier a strong flow should exist. I would also like to propose to call this type of rock glacier by the name of "special type". It was observed in mid-summer that this rock glacier produces a substantial amount of water and the thawed layer was about a meter thick and there was interstitial ice below. It is located between 3900 and 4400 m to the west of Aconcagua.

Sub-type P4: in the silt or clay stone slopes, which are weathering in fine particles, it is observed that protalus ramparts, of in very clear crescent shapes, are developing into debris bodies which contain a frozen core. Such protalus ramparts, which are changing into rock glaciers, are proposed to belong to type P4. For the Hindukush, GRÖTZBACH (1965) indicated that protalus ramparts (*Hangblockwulst* in German) are a transition to rock glaciers.

Debris covered glaciers or secondary rock glaciers: "*type S*"

Due to the fact that they are rock glaciers produced by the melting of the bottom layers of valley glaciers rich in debris (LLIBOUTRY, 1953—1955; BARSCH, 1969), (4, 5), it is proposed *that* such rock glaciers to be called *debris covered glaciers* or *secondary type S*. It was indicated that glaciers covered with debris should not be called rock glaciers (HUGHES, 1966; ØSTREM, 1971). Within this group, the following sub-types are differenciated:

Sub-type S1: under this category we are including the glaciers completely covered with debris. They are similar to BARSCH'S type 3 (1969) and CAPELLO'S type 1 (1960). From the superficial features it is seen that below the debris layer there is massive ice shown by thermokarst features, frozen lakes and dry depressions, crevasses, longitudinal bands and transversal arches (Pl. 4). The thermokarst feature is a term taken from the permafrost regions when a debris layer (active layer) melts the ice below. This thermokarst feature is the most conspicuous characteristic of the initial stage in the formation of the rock glaciers of the S type. Since the rock glaciers are related to vanishing glaciers it should be considered a typical periglacial process.

Sub-type S2: the terminal moraines left isolated after glacial surging are included under this category. They are moraines of ice and debris, which after a time change to a rock glacier type feature. In the Plomo region, the Helbling glacier advanced between 1910 and 1914 (HELBLING, 1919). In the aerophotographs taken in 1963 we observe a moraine-like feature with thermokarst lakes (average height 3500—

3800 m); but in the ones taken 11 years later the thermokarst features have disappeared, the form of the moraine is also vanishing and a mass of material is blocking the valley. Future surveys will have to be made in order to determine the evolution of the debris and ice body.

Rock glaciers affected by the action of glaciers: "type RGGl"

In the Plomo region there are two cases in which the surge action can be observed on rock glaciers; it is proposed that these to be classified: RGGl 1 and RGGl 2.

Sub-types RGGl 1—RGGl 2: in the mentioned region ice advances have cut or scraped the underlying rock glacier, and left a debris body at the foot of a cirque. Other evidences of the ice action are the lateral moraines and "hanging"rock glaciers at both sides of the isolated or shaved rock glacier. The rock glacier scraped by the ice advance will be called RGGl 1; and is equivalent to LLIBOUTRY's d (1955). The "hanging" rock glaciers at the moraine sides will be called RGGl 2. Such rock glaciers are no longer nourished by snow or debris avalanches.

Rock glaciers of mixed origin: "type RGMO"

Under this category we include rock glaciers which are in between the primary type in one extreme and the secondary at the other.

Rock glaciers of rapid motion: "type RGRM"

In the Plomo region a rock glacier described as the scraped type is observed to be moving more than 100 m per year. This was determined on aerophotographs taken in 1963 and 1974. As this rock glacier is at an unusually high rate, it is proposed it to be placed in a special category: rock glaciers with rapid motion.

FORMS, DIMENSIONS, MOTION AND OTHER CHARACTERISTICS

The sizes, shapes, the surface features, the motion rates and other marks are related to the origin of rock glaciers, their age and the climatic fluctuations which affected them.

Forms, dimensions and other surface markings

Rock glaciers of a primary type located at valley sides (Pls. 1—3) are more regular and smaller than the debris covered glaciers of the secondary type located at the bottom of the valleys (Pls. 4—5).

Secondary rock glaciers because of their origin and size are located at the foot of cirques and they flow along the valley trend. The majority of Chilean glaciers are secondary (LLIBOUTRY, 1956), due to glacier recession during the present century. A Chilean secondary rock glacier, the Cachapoal, is 9 km long; and the Horcones Glacier at the foot of the Aconcagua, that is in the thermokarst stage since 1919 (HELBLING, 1919), is. 7.2 km. The Tunuyan Glacier also in the same stage is 12 km long (LLIBOUTRY, 1956). Primary rock glaciers begin by flowing normally to the valley; if they grow large enough they will start to flow in the down valley direction. When they are growing, their sizes depend on the spacing of the avalanche chutes which feed them. In general, rock glaciers of the P type are 100—300 m wide and not more than 1000 m long.

The surface features of rock glaciers will depend on their origin and age. Primary rock glaciers have more regular surfaces than secondary ones (Pls. 1—5); the first have less patterned surfaces than the others; this might be attributed to the effect of the secondary's massive ice which promotes more flow of the surface regolith due to the smooth-ice-regolith interface. Most primary rock glaciers have longitudinal troughs and few transversal arches (Pls. 1—2). Secondary rock glaciers have both transversal and longitutinal features (Pls. 4—5). Secondary rock glaciers which are melting of the debris-rich valley glaciers have thermokarst lakes in their initial stages (CORTE, 1953; Pls. 2—4). It is proposed this stage to be called "thermokarst stage". This stage was observed when the superficial cover was only 10 cm thick on glacier ice; and it can last for many years depending on the location or exposure. Two airphotos taken in 1963 and 1974 of the Pan de Azucar Glacier indicate a shift of the belt or facies of thermokarst from the lower portion of the rock glacier to the upper part (Pl. 4). This can be attributed to the glacier recession during this time. When the surface cover of the rock glacier increases it develops patterns of transverse arches and longitudinal troughs (Pl. 5). Transverse arches are more frequent in the lower parts while in the higher parts the longitudinal predominate, merging with the talusses (LLIBOUTRY, 1955; CAPPS, 1910; WARHAFTIG and COX, 1959; POTTER, 1972). Both primary and secondary rock glaciers are bounded in their lower terminus by a steep face (Pl. 6) with slope angles from 35° to 45° (CAILLEUX and TAYLOR, 1954; TRICART and CAILLEUX, 1970; LLIBOUTRY, 1955).

Other morphological elements like lobes which indicate different periods of activity of the rock glacier (WARHAFTIG and COX, 1959, p. 343), are mentioned. Surging rock glaciers are not mentioned in the literature; however it is debatable whether or not the Plomo rock glacier surged 1200 m in 11 years. Tension cracks are also observed in rock glaciers (Pls. 4—5).

The cover, its origin and the frozen core

Available information indicates that the surface cover of rock glaciers contains the coarser elements, while at the contact with the frozen body the gravel, sand and silt are found (IVES, 1940, p. 1279; WARHAFTIG and COX, 1959, p. 383; POTTER, 1972, p. 3042; BENEDICT, 1973). LLIBOUTRY (1961 b, p. 218) writes that the presence of fine particles in the cover of rock glaciers is an evidence of youth; in later stages the fines are washed away by melt water. On the other hand evidence of rock glacier motion would be indicated by the presence of blocks on the surface (LLIBOUTRY, 1955; THOMPSON, 1962, p. 214; BARSCH, 1971 a). Geophysical soundings made all along a rock glacier (ice-cored, secondary type) showed a continuous increase of the cover thickness downslope (POTTER, 1972, p. 3039).

For primary rock glaciers the debris comes from the avalanche chutes that feed them; likewise in the case of the buried glacier (LLIBOUTRY, 1961 a) the debris comes from rock outcrops higher up.

For secondary rock glaciers or debris covered glaciers the surface debris comes from the basal parts of the rich-indebris glaciers. Different mechanisms have been proposed for the development of the debris cover: (1) fusion — when glaciers are thinning by melting the material dispersed within the ice remains on the surface (LLIBOUTRY, 1953: OUTCALT and BENEDICT, 1965); (2) debris can reach the surface along shear planes (CARRARA, 1972); however BENEDICT (1973) and WHALLEY (1974) do not believe that this holds in the Arapaho rock glacier that they studied. Most available information indicates that the longitudinal bands are connected to the deformed talus cones which feed debris to the rock glaciers.

The origin of the ice

The following mechanisms have been proposed for explaining the origin of ice in rock glaciers: (1) compacted snow produced by direct precipitation or wind drifting and avalanches (POTTER, 1972; WARHAFTIG and COX, 1959); (2) covering of firn by layers of debris (LLIBOUTRY, 1961 a) (3) glacier ice (LLIBOUTRY, 1953; OUTCALT and BENEDICT, 1965); (4) freezing of meltwater or rain (WARHAFTIG and COX, 1959). However this process was considered of little importance for ice-cored rock glaciers or secondary rock glaciers (OUTCALT and BENEDICT, 1965; POTTER, 1972); possibly this mechanism could be more important in primary rock glaciers; (5) the Balch ventilation effect, by which cold air tends to fill the voids of the blocky materials producing and preserving ice (THOMPSON, 1962; OUTCALT and BENEDICT, 1965); (6) a combination of Balch effect with freezing during winter and subsequent preservation by covering by solifluidal debris (JOHNSSON, 1974); (7) incorporation of surficial or underground ice (icings) in solifluidal materials (TYRRELL, 1910; WARHAFTIG and COX, 1959).

Motion

None of the published measurements differenciate between the movement of the surface debris (which is loose in summer) and the motion of the frozen core. The values given below are for the movement of the surface of rock glaciers, which is the motion of the whole body, cover and core (Table I).

CAILLEUX and TAYLOR (1954, p. 104—105) noted that in the Alps, glaciers were receding while rock glaciers were advancing. This is explained by the load of debris on top of the ice which increases flow-rate. Detailed measurements of rock glacier motion in Switzerland (BARSCH, 1969, p. 26) indicate that the rock glacier surface motion is not uniform. There are areas of maximum motion concentration[1].

Viscosity varies between 10^{14}—10^{15} Poises, while for glacier ice the values are 10^{12}—10^{14} Poises. The maximum shear stress for active rock glaciers varies from 1—2 bars; much grater than calculated from creep in solifluction (WARHAFTIG and COX, 1959, p. 383).

[1] The most measured by BARSCH was 5 meters per year (letter, 1974).

Table I

Author	Year	Place	Movement cm/y−1	Number of years observed
Chaix, A.	1923	Switzerland	130 surface 40 depth	10
Warhaftig and Cox	1959	Alaska Range	72 surface 48 front	8
Pissart, A.	1964	Chambeyron Alps	172	58
Outcalt and Benedict	1965	Colorado Front Range	9−19	1
Barsch, D.	1971	Engadin, Switzerland	10−100 surface	1
White, S.	1971	Colorado Front Range	5	5
Potter, N.	1972	Wyoming, USA	5−9	73

Thickness of the cover and melting

There is very little information regarding mass balance of rock glaciers: i.e. the relationship between accumulation of snow, ice and debris and their elimination from the rock glacier body (White, 1971, p. 43; Potter, 1972). A rock glacier in Wyoming (Potter, 1972) with an accumulation to ablation area ratio of 1:7 was believed to be ice-cored.

Table II

Annual block mov. on the surface of the RG. in m	Annual discharge of debris in m	Name of the rock glacier
5	215	Arapaho
6.6	269	Taylor
9.7	771	Fair

The block motion on the surface of 3 rock glaciers and the yearly discharge of debris at their fronts have been given by White (1973, p. 43; Tab. II).

It is a well known fact that a thin layer of dark particles on the ice surface will accelarate melting. The author's experiments in Greenland (Corte, 1960) have shown that a 5 cm gravel layer produced more melting than a 16 cm layer; but the uncovered ice melted much more. It seems that there is a critical thickness which produces more meltwater than uncovered ice. Østrem (1965, p. 32) states that a layer of about 2 cm of sand-gravel produces more melting than uncovered ice. Melting of ice below a cover is influenced by: (a) thickness, (b) colour, (c) cover diffusivity heat, (d) radiant input, (e) wetness in the layer.

For road constructions over the ice in the Thule Region, Greenland, the climatic conditions require a gravel cover of a meter to stop ice melting (Davis, 1971). Because of the meteorological conditions in the SW Yukon, (JOHNSSON, 1974), glacier ice melts even with a cover of 5 m of debris. At Sherman Glacier (BULL and MARINGUNIC, 1968), 5 cm of ice melted in a year below a 1.3 m cover, while uncovered ice melted 100—200 times more.

The depth of thawing in rock glaciers in the Central Andes was observed in January 1975 to be 1 m at 3500 m elevation; at 4500 m (CORTE, 1955) also in January, the thawed layer was only a few cm thick. In order to understand the hydrological importance of rock glaciers we should know more about the thermal conditions and behaviour of the debris cover (which in summer is loose, thawed); and also about the behaviour of the solid core, its accretion, motion, and whether there is freezing of meltwater of the bottom layer in contact with the frozen core.

THE EVOLUTION OF ROCK GLACIERS

THE EVOLUTION OF PRIMARY ROCK GLACIERS: "type P"

LLIBOUTRY (1955—1961 a) discussed the evolution of rock glaciers formed on taluses and produced by debris covering of firn layers. Rock glaciers formed on a talus and also fed by avalanches are believed to be similar to the talus glacier described by DI COLBERTALDO (1946). These are growing until they attain a certain mass and flow; GRÖTZBACH (1965) describes the growth of "Hangblockwulst" which afterwards gradually change to rock glaciers. It seems that the most similar process to the "Hangblockwulst" is BRYAN'S (1934) protalus ramparts. In the Mendoza Andes, above 3700 m, there is debris and block accumulation on the slopes (Pl. 3). They contain ice and in the summar are a water source. We observe all stages from the slope blocks to the rock glaciers.

In the Aconcagua region, in U-shaped valleys left by the glaciers, the talus cones are close to the glaciers while further down the taluses are deformed by ice flow. The talus cones are younger, they did not attain sufficient mass to flow. This type of rock glacier is similar to BARSCH'S type 1 (1969, p. 11).

THE EVOLUTION OF DEBRIS COVERED GLACIERS OR SECONDARY ROCK GLACIERS

The rock glaciers derived from the melting of rich-indebris valley glaciers are included in this type (BROWN, 1925; LLIBOUTRY, 1955; OUTCALT and BENEDICT, 1965; BARSCH, 1969; POTTER, 1972). BARCH'S type 3 belong to this category (1969).

After an altitudinal inspection of the distribution of glaciers and rock glaciers in the Andes's dry part, the following sequence is presented (as illustrated for the Rio Blanco area; Pl. 2: up.): (a) the uncovered ice facies, (b) below, a thermokarst facies, (c) further down as the debris thickness increases it becomes structured with a flow type of pattern like a cord or string, this is "structural debris", (d) further down as more ice melts the structured debris looses its form; the surface is smoother;

this is the "inactive facies", (e) even further down, as all the ice melts away the smooth surface is covered with vegetation, this is the "dead facies" of rock glaciers. Depending on elevations, exposure, slopes, etc., the development sequence can be complete or interrupted as shown in other examples: the rock glacier of Pl. 4 is wholy in the thermokarst stage. Rock glacier is in transition from thermokarst to the structural debris stage. Most of the inactive and dead stages are on the north facing slopes. The main characteristics of these different facies are as follows:

Bare glacier facies

Glaciers with positive balances show clean ice surface, and developed lateral and frontal moraines (Pl. 4: right).

Thermokarst facies

Thermokarst is used to express non-equal melting of ground ice, resulting in an irregular pattern of lakes and depressions. The thermokarst facies is located between the uncovered ice facies and the structured debris facies. It is characterized by lakes and irregular depressions (Pls. 2—4). These lakes lie where the debris cover is only 10—20 cm thick; and usually they show asymmetrical borders: the side exposed to the sun is gentle while the shaded side is steep.

Some thermokarst features are old lakes with their exposed side cut off (Pl. 4). It appears that the growth of these thermokarst features is very slow; the rock glacier of Horcones is in thermokarst stage since Helbling mapped it (1919). The Pan de Azucar thermokarst moved upwards in 11 years, due possibly to deglaciation during that time (Pl. 4). The thermokarst stage ends when the lakes begin to fill up with debris i.e. when the thickness of the cover increases. Round about Aconcagua the thermokarst is located on the north facing slopes between 4100—4800 m; on the south ones it is located between 4200—4700 m.

Rock glaciers facies with patterned debris

As the rock glacier surface debris cover increases it starts to flow, the thermokarst features disappear, and the debris begins to be patterned in string fashion (Pl. 5), with transversal arches and longitudinal troughs. This facies is located below the thermokarst facies and above the inactive stage facies. West of Aconcagua, this debris facies is observed on south facing slopes between 3300—3700 m (Pl. 4). In order to move rheologically in this stage the rock glaciers should be over 45 m thick (Warhaftig and Cox, 1959).

It is believed that in this stage the patterns of the surface materials are due mainly to the regolith slipping over the ice surface. In primary rock glaciers with no massive ice, no such elaborate systems of arches develop (see Pls. 1—2).

Rock glacier facies with collapsed surface due to ice melting, inactive, no motion

Below the structural debris facies, the surface are much smoother, less steep and with a less elaborate pattern. It is assumed that these smoother areas were active rock glaciers in the past, and now in a warmer climate with less ice the movement should be negligible (Pl. 2). This stage is equivalent to BARSCH'S type 2 (1971 b).

Dead rock glacier facies, no ice, smooth surface

Further down, the rock glacier surface is covered with vegetation; the surfaces are much smoother and cut by streams; this should be equivalent to types 2.1 and 2.2 which in the Alps are covered with vegetation below the timber line (BARSCH, 1971 b, p. 112).

MORPHOLOGICAL AND HYDROLOGICAL DIFFERENCES BETWEEN TERMINAL MORAINES AND ROCK GLACIERS FOR VALLEY SITUATIONS

According to our inventory of glaciers and rock glaciers it emerges that the glaciers motion is pushing the rock glacier debris to the valley sides, building lateral and frontal moraines. When the ice melts, the water cuts the end-lateral moraine leaving a river in the middle of the valley (Pls. 2—4).

When a rock glacier is formed, primary or secondary, the valley is chocked with debris in such a way that the river coming from above, flows at the rock glacier body side (Pls. 1, 2, 5).

HYDROLOGICAL SIGNIFICANCE OF ROCK GLACIERS

I have seen no published data on rock glacier hydrology. However, at this state of the research I can ponder on speculative assumptions; the following factors should be considered in the assesment of rock glacier hydrology: (a) the type of rock glacier, (b) the amount of melting produced below a debris cover, (c) the debris cover role as an accumulator of either snow or ice (produced by meltwater and refreezing at the top of the frozen core). It is very reasonable to assume that the rock glacier rough surface with they bouldery material, the very porous cover, and their elaborate patterns of arches and troughs are ideal places for snow to be trapped. As a matter of fact this rock glacier surface is a better accumulator then the very smooth surface of a glacier.

During 1974—1975 summer some qualitative information on rock glacier hydrology was obtained:

(1) primary, secondary and special type of rock glaciers carried significant amount of water which makes them a special research subject;

(2) usually rock glacier water drains underground due to the bouldery materials;

(3) the rivers fed by rock glaciers are clearer and have a more stable run-off than ice-snow fed rivers;

(4) under every protalus ramparts or "Hangblockwulst" or the buried type of rock glacier (LLIBOUTRY, 1961) spring waters emerge.

In the Alps, Schweizer (1968) reports significant amounts of water below the rock glacier in Braissekar (Sestrière).

As indicated above, the greatest difficulty in the investigation of rock glacier hydrology will be owed to the fact that run-off is underground.

THE FOSSIL STAGES OF ROCK GLACIERS*

Fossil rock glaciers are the debris accumulations located at the foot of mountains and valleys; produced by past geocryogenic processes and under the present warmer climate they are totally thawed. Due to the ice melt they are reduced in height. Depending on location and geological conditions they can be affected by erosion, cut by streams, and covered by talus cones or other sediments and by vegetation.

LOCATION, FORMS, SIZES

The fossil stages of Quaternary rock glaciers were described by Czajka (1955), Hövermann (1972), Barsch (letter 1974), Derbyshire (1973) and again by Czajka (written comm. 1975). More recent Holocene (neoglacial) rock glaciers were described by Madole (1972) and Mc Gregor (1972).

The following features are shared by the active and fossil stages of rock glaciers: (1) located in the shaded slopes of valleys and mountain sides, (2) a rock type which produces blocky materials, (3) places protected from stream erosion (Pl. 7).

The following characteristics are expected to be found in the fossil stages of rock glaciers:

(1) In plan view they can show tongue shapes with lobes and still steep front faces. There are longitudinal troughs and ridges at intervals of 10—20 m; depressions and intermediate lobes.

(2) Sizes vary from several hundred meters to a km or more.

(3) The blocky material has been extracted from a cirque type amphitheatre (Pl. 7). The cirques still show avalanche chutes or tracks which previously fed the rock glacier.

(4) The rock glacier lobes probably indicate the stages of activity (Pl. 7). In the lower parts there are ridges which look like glacier moraines. These lower ridges are more weathered and covered with vegetation than the upper ones. In the lower ones, soil is likely to have developed.

(5) Fluvial erosion is very likely to have cut the fronts and sides (Pl. 7).

(6) The rock glacier material, which may be called "rock glacier diamicton" is characterized by a heterogeneous mixture of materials (Pl. 8).

(7) The surface is likely to be very bouldery with finer materials below.

The Puna blocky debris covers (Keidel, 1922) located in the western side are interpreted as a part of the geocryogenic processes which produced the cryoplanation terraces in the middle, and the cirques in the eastern portion.

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* Since there is little information on fossil rock glaciers the author presents the following informations as a tentative approach in order to promote research in this field.

According to available information, the Quaternary geocryogenic activity, in this south-eastern part of South America, has produced features which are interpreted as rock glaciers: the stone runs of the Islas Malvinas are interpreted as fossil rock glaciers (ANDERSSON, 1924; CLARK, 1972; CLAPPERTON, 1975). For CLARK the debris which fed the stone streams moved and accumulated in the valleys as a motionless rock-ice mass. However ANDERSSON'S figures (1924) and CLAPPERTON'S photo (1975) indicate bands similar to the ones present in active rock glaciers. Farther north, in the Province of Buenos Aires's southern mountains, the blocky materials in the quartzitic sandstones are interpreted as fossil rock glaciers (Pl. 9). West of Mendoza City, between 1200 and 1800 m, average: 1500 m (Pl. 7) the fossil rock glaciers are located a couple of hundred meters below fossil protalus ramparts and gelifluction covers (Pl. 7). Farther north, in the Aconguija, Tucumán, fossil rock glaciers were reported by CZAJKA (1955) for 2600 m. Also CZAJKA (written comm. 1975) thinks that the previous researchers' "moraines" could be interpreted today as fossil rock glaciers.

We have no information so far of the ages of these rock glaciers; however considering the synchronism of the last thousand of years of climatic fluctuations in the northern and southern hemispheres (HEUSSER, 1966) and considering that these rock glaciers are cut by erosion (Mendoza) and partly covered by loess (Buenos Aires) and submerged by the rising sea level in the Malvinas, it is tentatively proposed that these rock glacier activities were a last glacial stage, comparable to the Wisconsin in the USA, and the Würm in Europe.

In summary, Argentinas fossil rock glaciers are as follow (tab. III):

Table III

place	latitude	altitude	rock	source
Aconquija	27	2600	—	CZAJKA, 1955
Mendoza	33	1500 1800	sandstone andesites	CORTE 1975
Southern Sierras Bs. As.	39	500	quartzite sandstone	CORTE, *et al.*, 1970–1973
Malvina Islands	52	0 and below	quartzite sandstone	CLARK, 1972

The above information was placed in a latitudinal-altitudinal diagram (Fig. 1) together with other rock glacier reports from Tasmania and Australia (DERBYSHIRE, 1973). Also some points were placed, based on the lower limits of gelifluction mantles of Africa (SPARROW, 1967; HASTENRATH and WILKINSON, 1973), and the stone streams of the Malvinas (ANDERSSON, 1924). The limits of the active rock glaciers are also indicated.

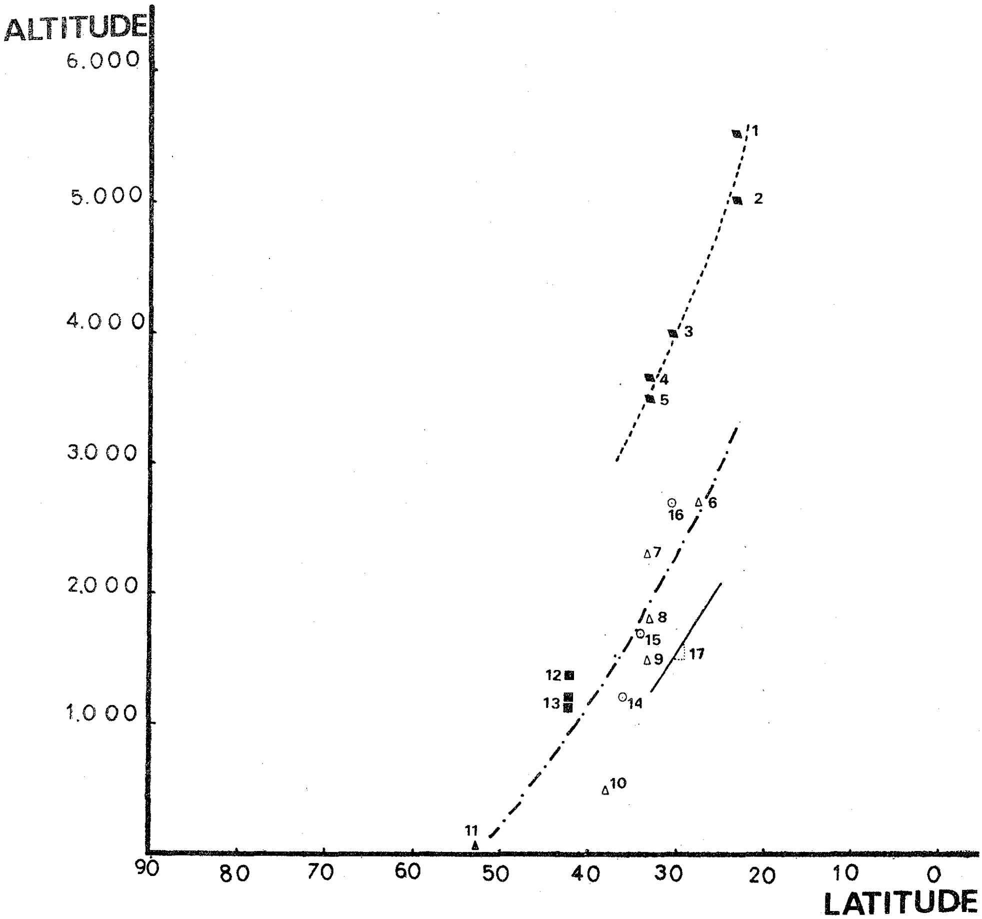

Fig. 1. Lati-altitudinal distribution of active and "fossil" Quaternary rock glaciers of the southern hemisphere

Upper Curve: active rock glaciers of Argentina (1-2), CATALANO (1926) Puna's Litoglaciaires; 3. KEIDEL (1922) boulder slopes of San Juan and la Rioja; 4-5. lower limit of rock glaciers of the central Cordillera in Mendoza (CORTE, 1975)

Middle curve: (6-7-8-9-10) fossil Quaternary rock glaciers of Argentina based on table III; 11. The Falkland Islands Stone rivers (ANDERSSON, 1924; CLARK, 1972); 12-13. and 14-15. fossil rock glaciers of Tasmania and Australia (DERBYSHIRE, 1973), 16. solifluction mantles in south Africa (HASTENRATH and WILKINSON, 1973), 17. slope of Pleistocene solifluction covers in south Africa (SPARROW, 1967)

PALEOCLIMATIC IMPLICATIONS OF ROCK GLACIERS

During their debris cover, rock glaciers are less sensitive to climatic fluctuations than non-covered glaciers; POTTER (1962) points out that an ice-cored rock glacier with a reasonable melting rate of 2.5 cm per year would take 2000 years to melt the 50 m of core ice. This implies that where clean glaciers have disappeared some rock glaciers might still contain ice and still be moving.

The glacier and rock glacier inventory under way at the Instituto Argentino de Nivología y Glaciología reveals that there are four levels of protalus ramparts at different elevations of the valleys; about an equal number of rock glacier levels on the north facing slopes, and also the same amount of buried soil levels (paleosoils) outside of the glaciated valleys. All this evidence is indicative of at least four climatic fluctuations during the Holocene Epoch (HOPKINS, 1975) which happened after the glaciers left the valleys. MADOLE (1972) indicates for the Colorado Front Range Neoglacial Era three intervals between glacier and rock glacier activity.

Since rock glaciers are formed at a mean annual temperature of about 0°C, and a yearly precipitation of about 1000 mm (LLIBOUTRY, 1956, p. 298) and 1200 mm (POTTER, 1962), mainly of snow, it is possible to use these values for comparison of the fossil stage climatic conditions. It is to be noted that an important factor in rock glacier climatic conditions is the amount of evaporation, fusion and refreezing of meltwater. These values cannot yet be quantitized.

Fossil rock glaciers in Africa (HÖVERMANN, 1972) located at 1100—2100 m and 21° S. Lat. and 17° W. L., are presently subject to a temperature of 12.5°C and 112 mm of annual precipitation. (This rock glacier is younger than the last glacial stage, and for that reason it is not included in the diagram of Fig. 1).

The fossil rock glaciers of the southern Sierras of Buenos Aires Province are also at about 12°C and a mean precipitation of 1000 mm. Mendoza's ones are presently at 15° or 16°C with about 400 mm of precipitation (Pl. 9).

It is to note that the age of primary rock glaciers formed in valleys left by glaciers increases down valley.

DERBYSHIRE (1973, p. 131) indicates for Tasmanian fossil rock glaciers at a temperature range of 6.5° relative to the present temperature and also a drier climate. This conclusion is extented to SE Australia.

All these fossil evidences are ascribed to be a past glacial stage and data is ploted in Fig. 1. These values agree with Pleistocene depression of the snow line (HASTENRATH, 1971, p. 257).

CONCLUSIONS AND RECOMMENDATIONS

Rock glaciers are produced by different processes: (1) accumulation of snow and debris below avalanche chutes, (2) deglaciation conditions when glaciers become debris covered and move slowly. Rock glaciers are a very conspicuous feature of the high and dry Andes, where there is a strong cryofragmentation and ice filling the voids; the ground ice facies correspond to the glaciers of more humid mountains. The uncovered glacier facies is located above the rock glacier. In isolated cases when the glaciers are advancing they take the rock glacier materials and build moraines out of them.

The rock glaciers' belt is much wider in dry cold zones than in cold humid zones where it thins out and disappears. In these dry regions it is possible to distinguish the terminal moraines produced by ice advances from rock glaciers: these in their advances build moraines, cut by the meltwater stream. With rock glaciers, on the other hand, the river coming from above usually flows at its side. Some times they are chocking the valleys. The water coming from rock glaciers drains underground within the surrounding bouldery materials. Taking as a model the high, arid Andes's rock glaciers, the following factors are considered significative in their formation: (1) climate, (2) rock type, (3) exposure, (4) abrupt topography under general deglaciation conditions, (5) deglaciation conditions for the debris covered glacier type.

(1) The climate with permafrost, with mean temperature below 0°C, is a necessary condition for the preservation of the frozen ice-core or debris below a covering layer of detritus. Precipitation is mainly snow, about 1000 mm. We do not know, as yet, if there is refreezing of meltwater on the frozen core's surface.

(2) Rock type is important because it determines the size of the blocks to build the rock glacier and the spacing of the avalanche chutes.

(3) Exposure is a fundamental variable which determines the existence of glaciers and rock glaciers according to altitude, valley orientation and rock type. Exposure is so important that it is possible to have glaciers in the cold faces (south facing slopes) of the mountains, and rock glaciers in the warmer northern or eastern faces.

Size, shape, surface features, and motion of rock glaciers are related to their genesis, their age and climatic changes to which they have been subjected.

Rock glaciers are classified according to morphology and origin as follows: (1) those produced by accumulation of snow and debris below avalanche chutes, in protalus ramparts, talus glaciers; (2) rock glaciers produced by accumulation of debris on top of glaciers, these debris covered glaciers are considered of secondary type; (3) those affected by the action of glaciers; (4) rock glaciers of mixed origin; and (5) rock glaciers of rapid motion.

The concept of facies is used to describe the different aspects which in this dry zone with intense radiation, characterize the sequence glacier—rock glacier according to altitude: (1) high up is the uncovered ice or glacier facies; (2) below that is the thermokarst facies; (3) further down the structural debris facies; (4) further down is the rock glacier's inactive stage, without motion; (5) below that is the dead stage without ice and covered by vegetation.

Fossil rock glaciers found under warmer climatic conditions point to temperature increase of some 10° to 15°C. The Puna de Atacama's boulder covers and Malvinas's stone rivers are interpreted as fossil rock glaciers formed during the Quaternary last cold stages.

Rock glaciers in the Andes, located in empty valleys left by the glaciers are postglacial, a product of the last 10,000 years of the Holocene Epoch. We distinguish inside the valleys and outside the area reached by the glaciers, several levels of rock glaciers, protalus ramparts and paleosoils, all of them related to the Holocene climatic fluctuations.

The posibility of using boulder fields, stone rivers, stone runs, etc. as fossil rock glaciers is indicated.

We need more information on: (1) the mechanism of incorporation of snow, ce, debris, and the water flow from the rock glacier body, i.e. the balance; (2) the temperature conditions in the cover and at least at the frozen cores' top; (3) the rock glacier hydrology will be determined by stages of rock glacier evolution, it is possible that the thermokarst stage will turn out to be the most active hydrologically; (4) due to the low activity of rock glaciers we expect that their materials will have less clay particles than the moraines of true glaciers; (5) the evolution of rock glaciers from their active to fossil stages.

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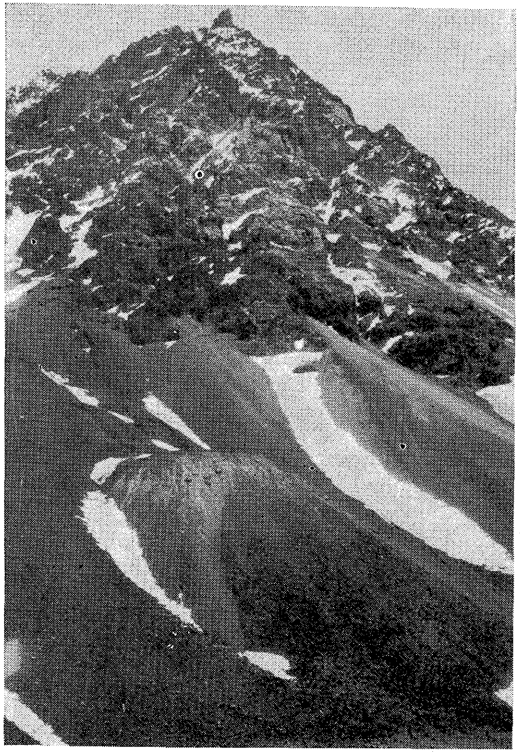
Photo by IFTA for IANIGLA (CONICET) in April 1972

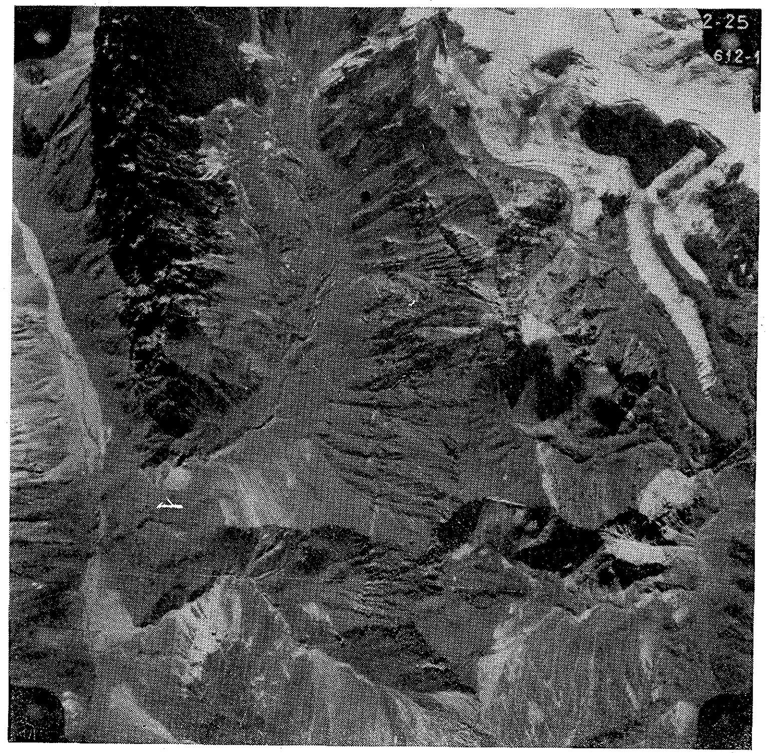
Pl. 1. Primary type rock glaciers developed in the south facing side of the valleys; in the north facing sides (warmer sides) solifluction prevails. Cordillera del Tigre Mendoza, Argentina

Photo by IFTA for IANIGLA (CONICET) in April 1972

Pl. 2. Upper part: the facies of rock glaciers: a) uncovered facies, b) thermokarst, c) structural debris, d) inactive stage. Center: rock glacier scraped by an ice-advance leaving isolated and cut rock glaciers on the sides



Pl. 3. Talus cone rock glaciers formed in the steep slopes of the valleys left by the glaciers; in front of the Matienzo station, 3700 m



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Pl. 4. A rock glacier in the thermokarst stage, west of the Aconcagua; this stage in a south facing slope is located between 4200 and 4700 m; place: Pan de Azucar

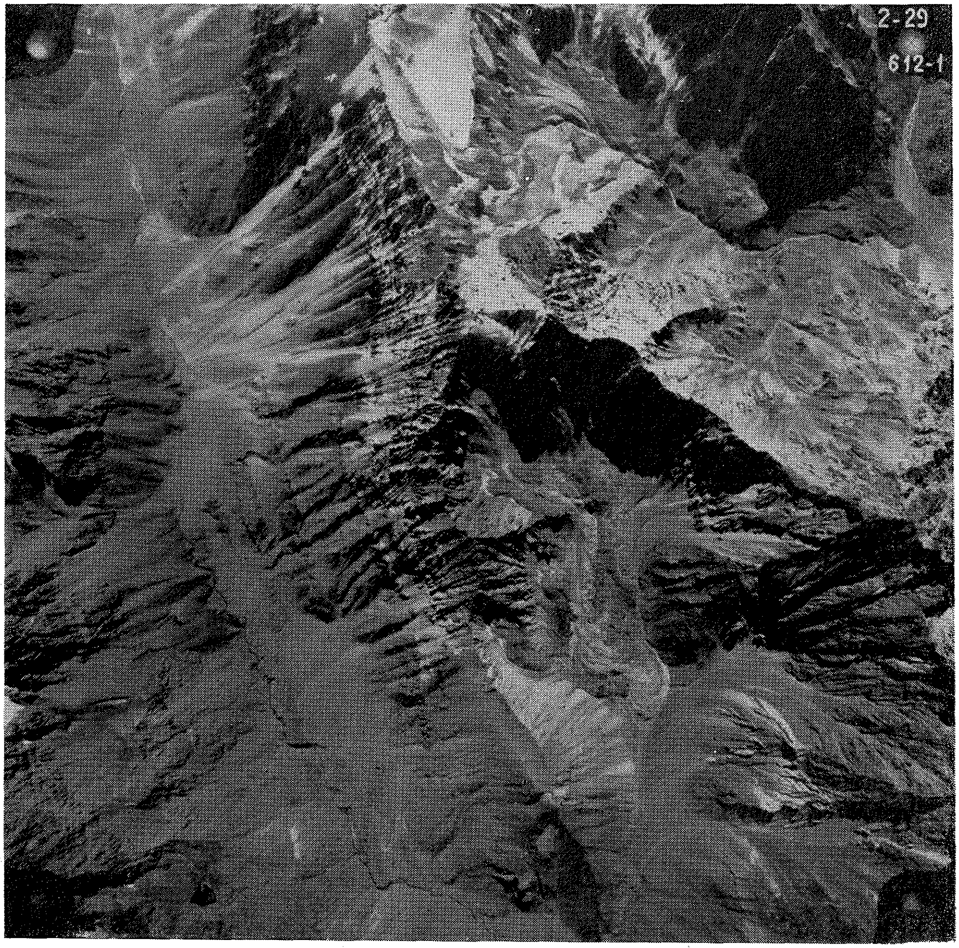


Photo by IFTA for IANIGLA (CONICET) in April 1972

Pl. 5. Rock glacier in the structural debris stage, between 3300—3700 m at the west of the Aconcagua, Place Tres Dedos

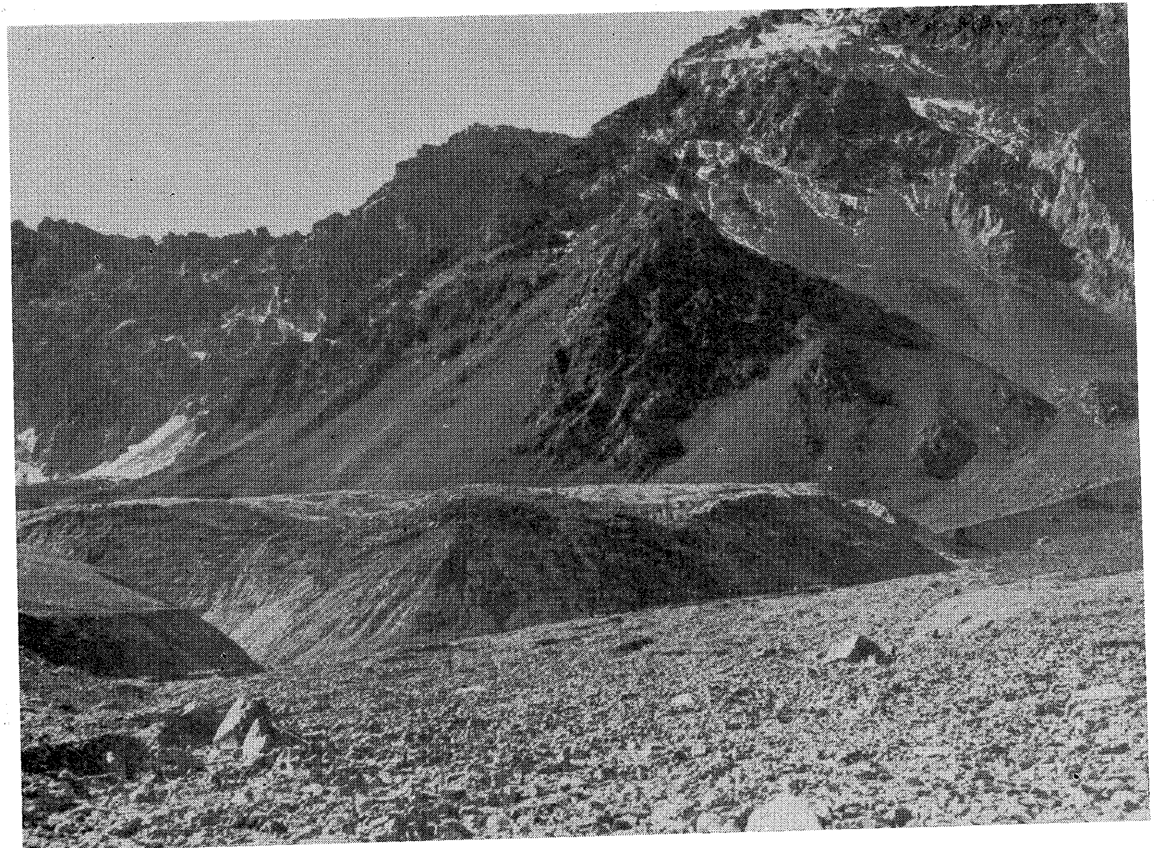
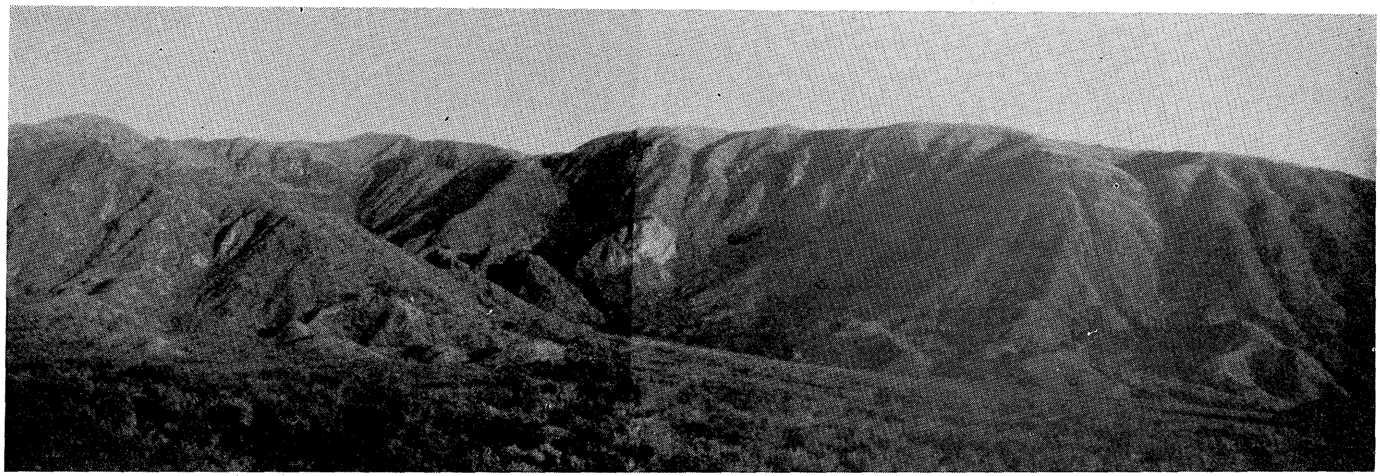


Photo A. E. Corte, April 1974

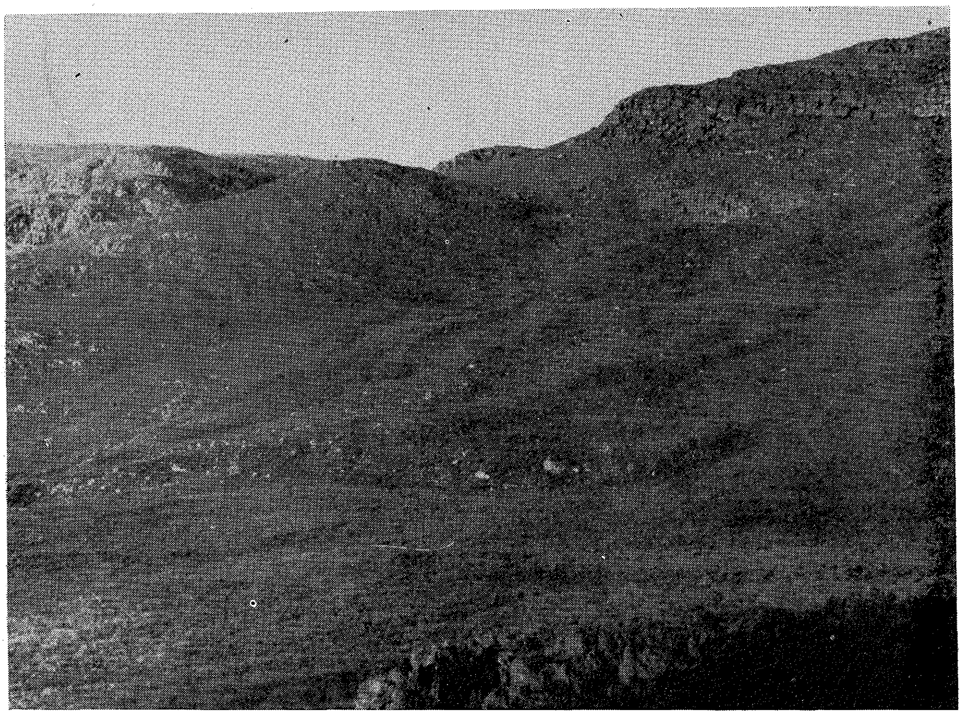
Pl. 6. Front view of the Tres Dedos rock glacier of Pl. 5
(Points 4—5 in fig. 1)



Pl. 7. Fossil Quaternary rock glaciers located at the west of the city of Mendoza at about 1800 m

note the upper part of the mountains with gentle slopes and at the upper left a protalus ramparts indicated by vegetation. Rock glaciers are in the south facing valley shaded places. Rock glaciers are cut by the stream erosion (point 9 in Fig.1)

Pl. 8. Rock glaciers diamicton; foto taken in a stream section of Pl. 7



Pl. 9. Fossil rock glacier in Sierra de la Ventana Prov. Buenos Aires at 38° S.L. and 500 m (point 10 of Fig. 1)