A FIRST APPROACH TO THE SYSTEMATIC STUDY OF THE ROCK GLACIERS IN THE ITALIAN ALPS

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SYNOPSIS This article is a preliminary review of the existence, distribution, and number of rock glaciers in the Italian Alps. The data analyzed, refer to several mountain groups chosen over the entire Alpine chain, and were obtained from the analysis of large-scale aerial photographs and field surveys. The rock glaciers are clearly very numerous in the areas with large crystalline massifs and appear to face prevalently northern directions. The consistent decrease in altitude in several parameters W to E seems to indicate a link between rock glaciers and general climatic characteristics of the southern flank of the Alps. The consistently different altimetric distribution of some of the parameters relating to active and inactive rock glaciers can be explained by the rise in altitude of the average annual isotherm of -2°C from the past to the present.

INTRODUCTION

According to the now classic definition by Wahrhaftig and Cox (1959), rock glaciers are tongue-shaped or lobate masses of poorly sorted angular debris lying at the base of cliffs or talus slopes or extending down-valley from the lower end of small glaciers. They are a characteristic form of permafrost and represent one of the most widespread and characteristic phenomena of the periglacial morphology found in mountainous regions where the climate tends to take on continental aspects. According to many researchers (Barsch, 1978; Evin, 1983; Haeberli, 1985; Belloni, Pelfini, and Smiraglia, in press) in the case of active rock glaciers, the mean annual isotherm of -2°C should represent the climatic requirement for their formation and maintenance as it represents the lower limit of discontinuous permafrost. It follows then that rock glaciers have been observed and described in all of the mountain chains on the Earth with climatic features suited to their formation, and that the scientific literature dedicated to them is extremely vast, as may be seen from several ample bibliographies (Barsch, 1983; Evin, 1983; Dramis and Smiraglia, 1986).

As concerns the Italian side of the Alps, several reports and descriptions regarding these forms were published in the 1950's and 1960's (Hermann, 1929; Nangeroni, 1929; Capello, 1947, 1959). They did not, however, approach complete detailed studies on their distribution and/or their morphological features.

Only recently have more systematic studies been planned within the "Glaciology" section of the CNR National Group on Physical Geography and Geomorphology. The preliminary results of these studies have already been published (Smiraglia, 1985; Dramis and Smiraglia, 1986; GNGFG, 1987). This paper has been written as part of this research program and is intended as a preliminary factual investigation into the existence, the distribution, and diffusion of rock glaciers in the Italian Alps. We shall also provide the most significant data collected on the morphological parameters which characterize rock glaciers, by distinguishing between the most frequent types and pointing out the principal differentiations appearing in the various mountain groups of the southern side of the Alps. This collection of data could thus represent a preliminary body of indispensable knowledge for future studies in the field of dynamic geomorphology, which investigates correlations between rock glaciers and climatic and litho-structural parameters.

The data on rock glaciers in the Italian Alps are given below in a preliminary summary. They were collected by numerous researchers participating in the National Group on Physical Geography and Geomorphology, who strove for as much homogeneity as possible in terms of the methodologies utilized. In the first stage of this study, the researchers carried out a selection of the mountain groups and sectors of the Italian Alps (listed below). The criteria adopted focused on selecting groups and sectors that would be as widely representative as possible of the different climatic, lithologic, and morphological situations characterizing the southern slope of the chain. Large-scale aerial photographs were then examined in order to identify forms that could be classified as rock glaciers. The rock glaciers were then reproduced on official large-scale maps (1:10.000 to 1:25.000), which made it possible to obtain numerous morphological and topographical parameters with good approximation. In the cases of areas of particular interest, field surveys were carried out with the purpose of identifying in a more detailed manner the most characteristic and widespread types of rock glaciers. A data sheet was compiled for each form and all the numerical and non-numerical elements were supplied, permitting a complete description.

CHARACTERISTICS OF THE ROCK GLACIERS IN THE ITALIAN ALPS

An area of approximately 20,000 square km

was examined using the methodology mentioned above. The area was subdivided into the various mountain sectors W to E as follows (fig. 1): Maritime Alps (1000km^2), Cottian Alps (800 km^2), Gran Paradiso (300 km^2), Monte Rosa (1400 km^2), Masino-Bernina (580 km^2), Piazzi-Cevedale (780 km^2), Brenta (180 km^2), Venoste Alps (1680 km^2), Noric Alps (1300 km^2), Dolomites (8100 km^2), Carnic Alps (3680 km^2). A total of approximately one thousand forms (987) was identified. A preliminary typological classification was carried out, distinguishing between active and inactive rock glaciers, those with uncertain activity, questionable forms and complex forms (that is, characterized by both active and inactive parts). This subdivision was carried out on the basis of some indirect signs of activity or inactivity which could be verified on the aerial photographs and compared with field observations recorded above all in the cases of the Gran Paradiso Group, the Cevedale Group, and the Dolomites. Forms held to be active are those with an absence of or almost completely lacking vegetation and which on the whole present a convex morphology with well-defined and steep margins, especially on the terminal area.

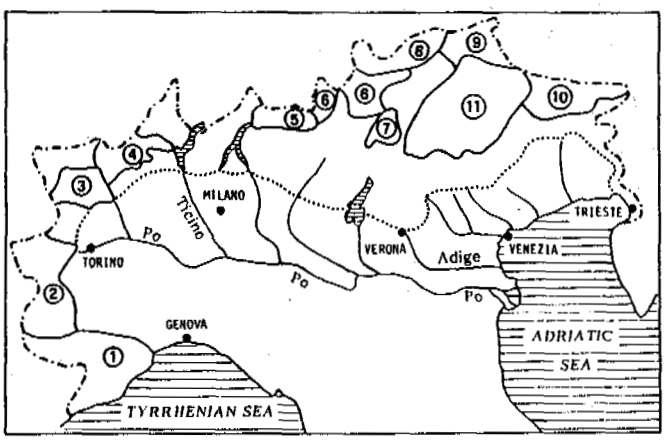

Fig. 1 Location of the mountain sectors. (Names of researchers and their respective Institutes between parentheses). 1) MARITIME ALPS (Tellini C. - Istituto di Geologia e Geografia, Università di Parma); 2) COTTIAN ALPS (Onorati M. - Dipartimento di Scienze della Terra, Università di Camerino); 3) GRAN PARADISO (Smiraglia C. - Istituto di Geografia, Università Cattolica di Milano); 4) MONTE ROSA (Ottone C. - Dipartimento di Scienze della Terra, Università di Pavia); 5) MASINO-BERNINA (Catasta C. - Dipartimento di Scienze della Terra, Università di Milano); 6) PIAZZI-CEVEDALE (Catasta C., Pelfini M. - Dipartimento di Scienze della Terra, Università di Milano); 7) BRENTA Group (Parisi G. - Istituto di Geografia, Università Cattolica di Milano); 8) VENOSTE ALPS (Palmentola G., Petruzzelli M. - Dipartimento di Geologia e Geofisica, Università di Bari); 9) NORIC ALPS (Castiglioni G.B., Mattana U. - Dipartimento di Geografia "G. Morandini", Università di Padova); 10) CARNIC ALPS (Meneghel M. - Dipartimento di Geografia "G. Morandini", Università di Padova); 11) DOLOMITES (Carton, A., Voltolini C. - Istituto di Geologia, Università di Modena; Castiglioni G.B., Pellegrini G.B. - Dipartimento di Geografia "G. Morandini", Università di Padova).

On the whole, 131 active forms were identified (13%), 449 inactive forms (45%), 215 with uncertain activity (21%). The remaining 21% is made up of complex forms, which clearly represent a minority, and questionable forms. Although the latter cannot be defined as rock glaciers in the usual sense of the term, they do show some morphological affinities with them. Distribution is very differentiated in the various mountain sectors and groups. The greatest number of forms was observed in the Noric Alps (218, that is 22%, taking all types into account), followed by the Cevedale massif (183) and the Venoste Alps (172). In contrast, the number of forms identified in the Carnic Alps (15) and in the Brenta Group (8) was very limited (fig 2). The highest density of forms

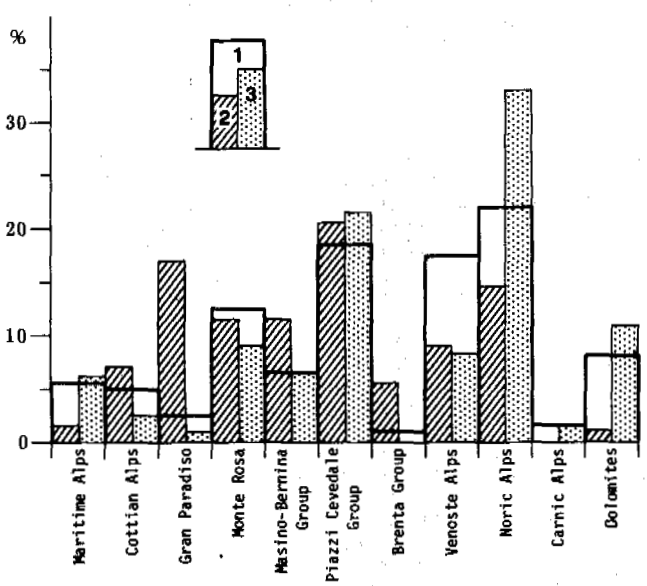

Fig. 2 Distribution of the rock glaciers in the various mountain groups in the Italian Alps. 1) all of the rock glaciers; 2) active rock glaciers; 3) inactive rock glaciers. (The percentages refer to each individual category.)

may be noted in the Piazzi-Cevedale Group (0.234 R.G./km^2), followed by the Noric Alps (0.167 R.G./km^2), and the Masino-Bernina Massif (0.106 R.G./km^2). The lowest density may be noted at the outermost borders of the chain in the Maritime Alps and in the Carnic Alps respectively. The majority of active rock glaciers can be observed in the Piazzi-Cevedale Group (21% approximately), followed by the Gran Paradiso and Monte Rosa Groups (approximately 17% for both) (fig. 2).

At any rate, a greater number of active forms is observable in the mid-western sector (70% of the total number of active rock glaciers). As far as the vertical distribution of the rock glaciers in the Italian Alps is con-

cerned, taking into account all the forms examined and all the data collected, it was found that the altitude of the fronts varies from a maximum of 3150 m (in the Gran Paradiso Group) to 1550 m (in the Carnic Alps) (fig. 3). The mean altitude of the fronts evidently tends to decrease from the westernmost groups to the eastern ones (fig. 3). Another interesting finding concerns the altitudes of the fronts of

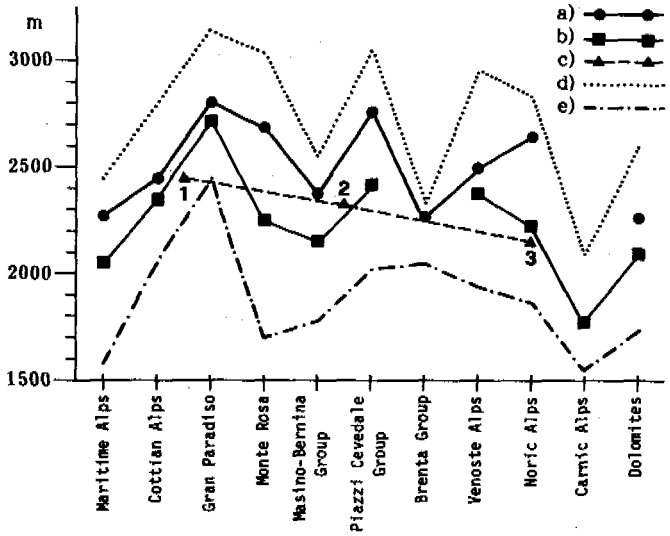

Fig. 3 Patterns of the mean maximum and minimum altitudes of the rock glacier fronts in the various mountain groups. a) mean altitudes: active forms; b) mean altitudes: inactive forms; c) mean altitudes of the active forms, inactive forms and forms with uncertain activity in the western (1); central (2); and eastern (3) sectors; d) maximum altitudes amongst all the rock glaciers; e) minimum altitudes amongst all the rock glaciers.

the active rock glaciers, which range from 3150 m in the Gran Paradiso Group to 2150 m in the Brenta Group. They are consistently higher than those of the inactive rock glaciers (which range from 2900 m in the Gran Paradiso Group to 1550 m in the Carnic Alps) (fig. 3). The forms identified are situated in basins circumscribed by ridges, the altitudes of which range between 3600 m (Monte Rosa) and 1750 m (Maritime Alps). In the case of this parameter as well, it may be noted that both the maximum and minimum altitudes of the highest peaks of the basin are almost always higher in correspondence with the active forms with respect to the inactive forms. With regard to the area of the rock glaciers, a marked variability was observed in the data collected. Taking into account all of the forms identified, one finds rock glaciers, in fact, ranging from those of very limited size (2500 m^2 in the Gran Paradiso Group) to those over one-half km^2 in area (for example, 843000 m^2 in the Cottian Alps, 690000 m^2 in the Dolomites, 600000 m^2 in the Masino-Bernina Group). In this case as well, it is possible to point out a considerable difference between active and inactive forms. The areas of the inactive forms are on the average, greater than those of the active forms. The last two parameters taken into consideration were length and longitudinal slope. As was observed in the case of area, there is considerable variability in the data concerning length. The greater lengths were identified in the Cottian Alps (2200 m) and in the Dolomites (2125), whereas minimum lengths (50m) were reported in the Gran Paradiso and Monte Rosa Groups. This variability seems to be less marked in forms of the same typology from a dynamic point of view: inactive rock glaciers prove to be longer than active ones in most of the mountain groups. Longitudinal slope, ranging between 10 and 110 %, also appears to be extremely variable, although no particular correlations with different types of rock glaciers were revealed.

The findings on aspect supplied some precise indications. Forms facing northern quadrants predominate. As may be observed in fig. 4, 46% of all the forms is concentrated in the NW-NE sector. The remaining 54% is distributed in the other sectors with a maximum of 15% facing S. The same distribution is rigorously maintained in the analysis of both active and inactive forms.

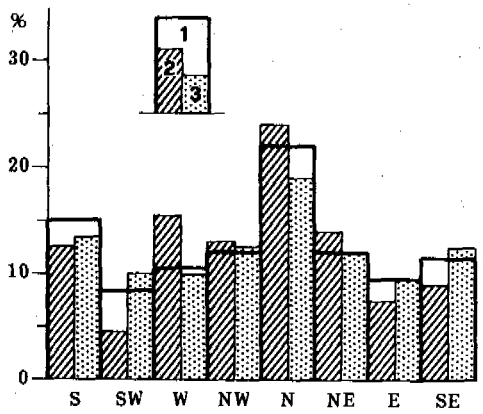

Fig. 4 Distribution of the aspect of the rock glaciers. 1) all of the rock glaciers; 2) active forms; 3) inactive forms. (Percentages refer to each individual category).

The rock glaciers are located prevalently in cirques (43%) and on slopes (42%). The percentages are markedly lower for those located in the bottoms of valleys and in gorges. When the forms were analyzed separately according to the different types of activity, it was found that the active forms are prevalently located in cirques (50%) and only to a lesser extent on slopes (30%). The percentages for forms with uncertain activity (49% in cirques and 36% on slopes) approach the same levels as those for the above-mentioned active forms. There is a clear difference, however, with respect to the inactive forms (which yield percentages of 41% and 44% respectively) (fig. 5).

The rock type from which almost all rock glaciers originate is represented by metamorphites (82%) (fig. 6). They are principally calc-schists, micaschists, green stones, phyllites, and gneiss which make up some of the most impressive crystalline massifs in the

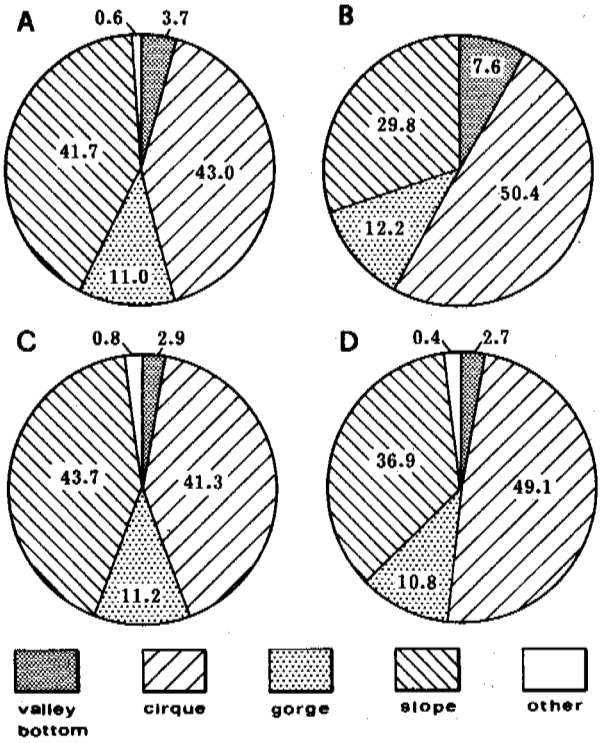

Fig. 5. Location of the rock glaciers (in percentages). A) all of the rock glaciers; B) active forms; C) inactive forms; D) forms whose activity is uncertain.

Alps, such as the Gran Paradiso, Monte Rosa, the Bernina, the Cevedale, and the Venoste and Noric Groups. Forms originating from other rock types are clearly less common (such as the carbonate rocks in the Dolomites and the plutonites in the Masino Group).

From the point of view of geomorphological lineaments, some of the more evident features are the presence of a steep front, curved furrows, and a well developed tongue. The latter is more frequent in the inactive forms.

The proximity of rock glaciers to various types of glacial forms and moraines appears to be significant. Taking into account all the various forms observed, it may in fact be noted that almost half are situated near end moraines (46%) and another large percentage (38%) present semi-permanent snow banks in the upper part (fig.7). Considering the forms by activity, the percentages change remarkably. Active forms are connected with semi-permanent snow banks (53%), glacierets (20%), and moraines (19%). Inactive forms, on the other hand, prove to be linked prevalently to moraines (82%).

As regards relationships between the position of the front and local vegetation limits, it was observed that the active rock glaciers are above the vegetation (85%). In contrast, the inactive forms descend within the zones of grassy vegetation (51%) and tree-growth also (21%)(fig. 7). In those types of rock glaciers with uncertain activity, the front is located above and below the upper limit of the grassy vegetation with the same percentage.

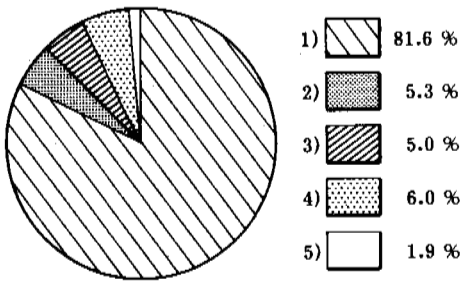

Fig. 6 Distribution of the rock glaciers according to rock type. 1) metamorphites; 2) plutonites; 3) vulcanites; 4) carbonate rocks; 5) other sedimentary rocks.

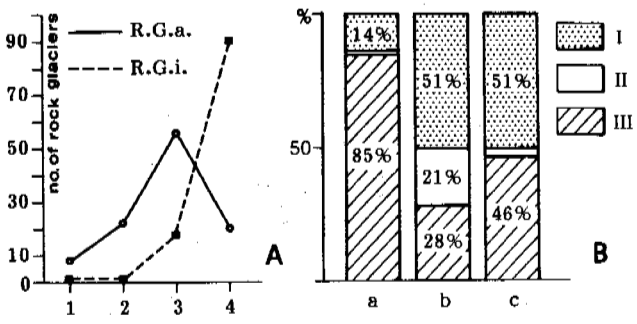

Fig. 7 A: Relation between active rock glaciers, inactive rock glaciers, glacial forms and moraines located above them. R.G.a.) active rock glaciers; R.G.i.) inactive rock glaciers; 1) glaciers; 2) glacierets; 3) semi-permanent snow banks; 4) morainic deposits; (the number of forms identified is indicated on the y-ordinate axis).
B: Relations between the position of the rock glacier fronts and the local vegetation limits; (The percentages refer to each category). a) active forms; b) inactive forms; c) forms whose activity is uncertain; I) front below upper limit of the continuous grassy vegetation; II) front below the upper limit of tree-growth; III) front above all vegetation zones.

REGIONAL DIFFERENTIATIONS

The principal typological differences between rock glaciers in the various mountain sectors examined, can be generally summarized in the following manner. The first significant finding is the limited number of forms and above all, their limited density in the outermost zones of the Alpine chain. For example, in the Maritime Alps, where, from the lithological point of view, the gneiss of the Argentera alternate with permocarboniferous porphyrites and Triassic and Jurassic limestones of the Marguareis, over the area examined which is over 1000 sq. km, only fifty forms (approximately) were identified. Of those forms, at least eighteen can be included amongst rock glaciers only with some reservations. The remaining are

almost all covered with discontinuous vegetation and present a morphology with curved furrowed tongues and distinct collapse phenomena (funnel-shaped hollows); the fronts descend even below 2000 m with a minimum of 1575 m. On the other extremity of the chain to the east, in the Carnic Alps, rock glaciers are an even rarer phenomenon (in over 3500 sq. km in fact, approximately fifteen forms were identified and they are of limited size, usually situated on the bottom of the cirques). This is a region that is characterized by abundant precipitation (i.e., the highest rate of rainfall in all of Italy), with a snow line that is rather low, and where even the lithological and morphological elements are not favorable for the diffusion of rock glaciers. The limited height of the reliefs (the peaks, which are prevalently made up of carbonate rocks, do not exceed 2800 m) is accompanied by sharp crests and very steep slopes, which reduce still further the areas suited to rock glaciers.

The situation in the great crystalline massifs is quite different. Their summits exceed 4000 m in altitude in the western and central sectors (Monte Rosa, Gran Paradiso, Bernina). In the eastern sector, on the other hand, the main peaks rarely descend below 3700 m (Cevedale) and 3500 (Venoste and Noric Alps). In these areas, the rock glaciers truly become an essential element of the mountain landscape, situated immediately between the zone occupied by the glaciers and that occupied by the tree-growth. In the Gran Paradiso Group, for example, where from a lithological point of view, gneiss, calc-schists, and green stones dominate, about thirty rock glaciers have been identified in an area of over 300 sq. km. Medium- to large-sized forms prevail and they have very regular tongues. Their surfaces are characterized by dozens of large concentric arches with a distinct scarp border. Metamorphic schistose rocks, such as gneiss, micaschists, and prasinites, feed the numerous rock glaciers in the Monte Rosa Group as well and are prevalently situated somewhat distant from the amply glaciated nucleus of the massif, especially in the case of the inactive forms.

In the regions of the Bernina and the Cevedale Groups, where 62 and 183 rock glaciers were identified respectively, (in the case of the Cevedale Group, the second largest number of rock glaciers after the Noric Alps was identified, but their density is highest there), further confirmations of the influence that lithology has on the distribution of these forms are provided. These forms are in fact quite rare in the Masino area, slightly west of Bernina Group, where intrusive rocks (granodiorites) prevail. On the contrary, they are quite numerous in those areas (Antognasco Valley, Grosina Valley, Rezzalo Valley) where schistose rocks (gneiss and micaschists) outcrop. In addition, the complex typology of the rock glaciers in this sector should be emphasized. Along with the classic tongue or lobe forms with steep fronts and curved or folded surface furrows, other types may be observed. For example, there are very extensive forms in a transversal direction, located in terminal cirques at the base of steep rocky walls, with only slightly inclined surfaces covered with large boulders and funnel-shaped hollows and inactive forms with steep fronts and internal depressed areas, but abundant in isolated blocks. In addition, rock glaciers with overlying lobes of different ages may be observed and also forms consisting in rejuvenated lobes with regular curved furrows at the base of the moraines dating from the Little Ice Age.

Research on some of the rock glaciers in the Cevedale Group has been done on the part of the National Group of Physical Geography and Geomorphology (GNGFG, 1987). This research has dealt with the examination of the dynamics, genesis, and structure of these forms. The eastern rock glacier in the Val Pisella has been studied in detail. It presents a classic tongue form with a length of 400 m approximately. The front, the inclination of which reaches 37 degrees, stops at 2830 m and is made up for the most part of fine material (small stones and sand). Above the front the visible part of the rock glacier is completely made up of large blocks that are distributed chaotically. However, regular longitudinal and transversal structures may be distinguished on the surface. The transversal structures are principally made up of arches with the hollow facing up valley, which demonstrates the compressive flow of that part and the differential velocity. The longitudinal structures are visible on the borders, in the form of elongated narrow ridges, and in the central part, in the form of fractures and trenches, which extend for dozens of meters. The arrangement of the clasts on the surface of the accumulation seems to suggest the existence of processes of solifluction in the distal portion of the rock glacier and of a block stream that is rather rapid in the proximity of the lateral margins and in the more elevated part. The presence of fractures and steps on the surface may be retraced to the overall movement of the mass and to local collapse phenomena due to melting of the buried ice.

The overlapping of many protruding lobes with steep fronts was observed in the Noric Alps and in the Venoste Alps where the highest number of forms identified is concentrated (22% in the Noric Alps, and, together with the rock glaciers in the Venoste Alps, approximately 40% of the total in the Italian Alps). Both regions are made up of metamorphic rocks (principally gneiss, micaschists, phyllites, calc-schists). The forms considered to be active are clearly a minority (6% of the total in the Venoste Alps and 10% in the Noric Alps). In this second area, they are located in places where glaciers are also present. Sometimes, however, the rock glaciers are found in marginal positions or in locations little suited to glaciers; the highest altitude of the surrounding peaks often exceeds 3000 m, whereas the lowest altitude of the frontal margins ranges between 2800 m and 2400 m. The inactive rock glaciers, on the other hand, are found in very extensive areas where mountain peaks rarely exceed 2800 m and usually reach 2500 m (approximately). One of the factors favoring the notable diffusion of rock glaciers in this area seems to be the existence, within limited distances from the crests which supply deposits, of surfaces that are not too inclined and which are capable of receiving such deposits, which could have resettled with the typically slow movement of these forms.

The Dolomite sector is characterized by the almost complete absence of active forms (only 2 out of the 55 definite forms identified) and by an equally low density of forms per sq. km. The altitudes of the frontal margins of the active rock glaciers descend to

2225 m, whereas the inactive ones reach 1750 m. Forms deriving from sedimentary rocks are quite rare. In fact, although the latter outcrop abundantly in the Dolomite sector, of all the forms identified, only 12 are related to those rock types. Porphyries, on the other hand, appear to be quite suited to the formation of rock glaciers, as is observable in the Lagorai Group. The rock glaciers in the Dolomite sector prove to be prevalently located on slopes and, to a lesser degree, in cirques and in valleys respectively. They present tongues that are fairly developed but not very long, prevalently lowered, and with the presence of curved furrows and frontal margins that are almost always distinct. The presence of an inactive form in this sector should also be noted. It is one of the largest in the entire Italian Alpine chain and is just slightly smaller than the largest rock glacier of uncertain activity in the Cottian Alps. The tongue is 1250 m long, with several funnel-shaped hollows and numerous curved and irregularly bending furrows which are separated by ridges 10-12 meters high. Three different phases of activity are evident, one inside the other. The oldest part of the rock glacier appears to be almost entirely covered with tree-growth and presents several hollows that are dozens of meters in diameter. However, the general morphology of the three overlapping forms appears to be very much lowered.

CONCLUSIONS

Above all, this preliminary and general analysis of the morphological features of the rock glaciers in the Italian Alps permits the identification of the regions in which active forms are clearly prevalent. They are the great crystalline massifs, in which the lithological factor must evidently play a fundamental role. Another determining factor in the distribution of the active rock glaciers may undoubtedly be seen in their aspect. The northern sectors, in fact, appear to be markedly privileged when the number and size of the rock glaciers are considered. The uniform lowering of the altitude of the frontal margins from the west to the east may be an indication of a link between the distribution of the rock glaciers and the general climatic characteristics of the southern side of the Alps, where there is a parallel decrease in the climatic snow line. The influence of climate and particularly of its variations in time, may find further confirmation in the different altitudinal distribution of several parameters, such as the altitude of frontal margins and the maximum altitude of the basins that contain both active and inactive rock glaciers. In fact, besides being characterized by frontal altitudes that are higher than those of inactive rock glaciers, active rock glaciers are situated in basins that are enclosed by peaks that are higher than those which enclose basins where inactive rock glaciers are found. More specifically, the rise in altitude of the mean annual isotherm of -2° C, caused by the changes in climatic conditions, no longer permitted the formation and conservation of discontinuous permafrost in areas below this altitude limit. This determined the fossilization of the rock glaciers existing there and caused the rise of the vegetation line, as is amply demonstrated by the greater part of the inactive forms. The latter, in fact, very often prove to be located below the upper limit of the continuous grassy vegetation and sometimes below that of the tree-growth line, and are in most cases connected with morainic deposits.

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