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AREAL DISTRIBUTION OF ROCK GLACIERS IN THE ARGENTERA MASSIF (MARITIME ALPS) AS A TOOL FOR RECENT GLACIAL EVOLUTION RECONSTRUCTION

ABSTRACT: RIBOLINI A., *Areal distribution of rock glaciers in the Argentera Massif as a tool for recent glacial evolution reconstruction.* (IT ISSN 0391-9838, 1999).

The areal distribution of rock glaciers on the Italian side of the Argentera Massif is weakly irregular and clustered. The factors that determine the characteristics of irregularity and clustering are the orographic framework and the presence of areas in which the occurrence, or recent disappearance, of glacial conditions has inhibited the development of the rock glaciers. The sectors of relief that interrupt the continuous presence of the rock glaciers are currently influenced by glacial conditions (Clapier-Maledia-Gelas zone) and by recently extinct glaciation (Argentera zone). In these sectors the rock glaciers are found only at high altitudes (higher than 2.570 m), while on the remaining reliefs of the Massif they are present in various generations from 2.400 m to 2.600 m. In first analysis, the areal distribution of the rock glaciers can contribute to the understanding of the deglaciation modality of the Argentera Massif.

KEY WORDS: Rock glacier, Areal distribution analysis, Argentera Massif, Maritime Alps.

RIASSUNTO: RIBOLINI A., *La distribuzione areale dei rock glaciers del Massiccio dell'Argentera (Alpi Marittime) come strumento per la ricostruzione dell'evoluzione glaciale recente.* (IT ISSN 0391-9838, 1999).

La distribuzione areale dei rock glaciers del versante italiano del Massiccio dell'Argentera é irregolare e debolmente clusterizzata. I fattori che determinano le caratteristiche di irregolarità e clusterizzazione possono essere considerati l'assetto orografico e la presenza di aree in cui la presenza, o la recente scomparsa, delle condizioni glaciali ha inibito lo sviluppo dei rock glaciers. I settori del rilievo che interrompono la presenza continua dei rock glaciers sono attualmente interessati da condizioni glaciali (zona del Clapier-Maledia-Gelas) a da un recentemente estinto glacialismo (zona dell'Argentera). In questi settori i rock glaciers sono posti esclusivamente a quote elevate (superiori ai 2.570 m), mentre sui rimanenti rilievi del Massiccio sono presenti in più generazioni dai 2.400 m ai 2.600 m. In prima analisi, la distribuzione areale dei rock glaciers può fornire un contributo per la comprensione della modalità di deglaciazione del Massiccio dell'Argentera.

TERMINI CHIAVE: Rock glacier, Analisi di distribuzione areale, Massiccio dell'Argentera, Alpi Marittime.

INTRODUCTION

Analysis of the distribution of rock glaciers is generally accepted as a tool for the reconstruction of the extension and dynamic evolution of the glacial environment of a mountain relief. The relationships between the climatic significance of the rock glaciers (isotherm –1 C° corresponding to the front) and the variables that control the position of the ELA of a glacial tongue have been extensively analysed (i.e. Haeberli, 1983; Omhura & *alii,* 1992) and recently verified also in the Central Apennines (Giraudi & Frezzotti, 1997).

On the Italian side of the Argentera Massif 71 rock glaciers have been identified, distributed at various altitudes, in an area of about 200 km^2 (Ribolini, 1996, 1997a, 1997b). The data regarding altitude of the fronts, as well as other topographic characteristics, can be find in the Rock Glaciers Inventory of Italian Alps (Ribolini, in Smiraglia & Guglielmin eds., 1997).

In recent years hypotheses have been formulated regarding the extensions of the Pleistocene and Holocene glaciers for the Italian side of the Argentera Massif: in the last glacial maximum the glacial front extended to 790 m a.s.l. in the Gesso basin (Federici & Pappalardo, 1991) and at least to 1000 m in the basin of the Vermenagna (Federici, 1994). Some Late Glacial stages have been identified in the valleys and at present an analysis of the historical moraines and of the Little Ice Age using lichenometric datings is in progress. Little is known about the Holocene cold phases, except for some hypotheses suggested by Pappa-

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lardo (1997). The present evolution (last century) has been reconstructed by Federici & Pappalardo (1995).

The aim of this short communication is to verify if the areal distribution of the rock glaciers can be used as a contribution to the understanding of the deglaciation modality of the Argentera Massif.

AREAL DISTRIBUTION ANALYSIS

The rock glaciers are distributed along the axial chain, but also in corrispondence of internal areas prevalently in the SW (Rocca dell'Abisso) and NE (M. Matto) sectors of the study area (fig. 1). However, the distribution along the axial chain shows a gap in correspondence with the more southerly reliefs; there are no rock glaciers also in the central internal area, corresponding to the sector of Argentera. A statistical approach has been used (Luckman & Crockett, 1972; Chueca, 1992) in order to verify if the areal distribution is uniform, random (Poisson) or clustered.

Testing uniform distribution - The study area was divided into N = 14 equal size sub-areas (4,5 km^2), such that each sub-area contains a number of rock glaciers. In a uniform distribution each sub-area can be expected to contain the same number of rock glaciers (λ = 71/N). The hypothesis of no difference in the number of points per sub-area between uniform (expected) and not uniform distribution can be tested using chi^2 test of goodness-of-fit (tab. 1).

The expected distribution is 5.07 rock glaciers per subarea (with a standar deviation δ = 4,007) and the test has 12 degrees of freedom (N - 2). The null hypothesis is rejected at the 10% significance level (chi^2 = 18.57, critical value = 18.55). The test of chi^2 shows a value that only just goes beyond the limit of significance for a normal distribution, indicating therefore a weakly non-uniform type of distribution.

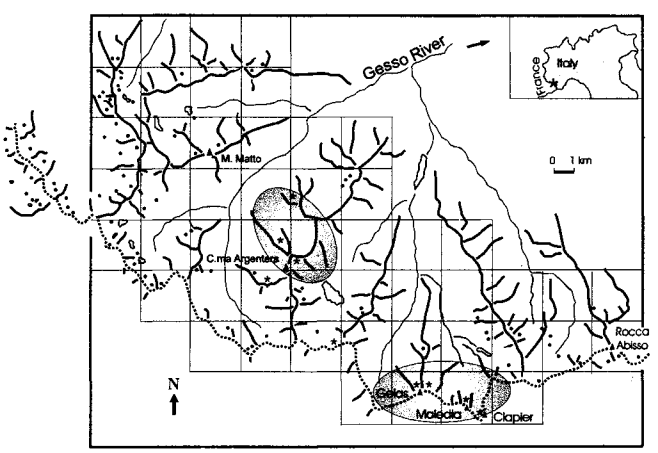

FIG. 1 - Rock glacier distribution in the Argentera Massif (Italian side). Points: rock glacier location; asterisk: active glaciers, glacierets and extinct glacier location.; grisè: areas with few or no rock glaciers.

TABLE 1 - Number of rock glaciers per sub-area and standarized form ($Z = n_i - (\lambda/\delta)$ for chi^2 test)

n° subarea	n° rock glaciers	rock glaciers Z form
1	12	1.72
2	2	-0.76
3	14	2.22
4	3	-0.51
5	3	-0.51
6	9	0.98
7	3	-0.51
8	4	-0.26
9	1	-1.01
10	4	-0.26
11	1	-1.01
12	3	-2.24
13	9	0.98
14	3	-0.51

Testing random distribution (Poisson distribution) - Rock glaciers distributed at random across an area can be modelled with Poisson distribution analysis. The area must be sub-divided into a greater number of equal size sub-areas (T = 51), to make the statistical test as efficient as possible (fig. 1). Then, we can count the number of sub-areas containing no rock glaciers, exactly one rock glacier, two rock glaciers and so on. The maximum number of rock glaciers contained in a sub-area is 8. If the rock glaciers are positioned with a random pattern, the probability (P) of the occurrence of sub-areas with r rock glaciers is

$$P(r) = (\lambda^r/r!)\, e^{-\lambda}$$

where λ is the mean number rock glaciers per sub-area (71/T, density of rock glaciers). The expectation (E) of an event r in a Poisson-type distribution can be calculated transforming the probabilities into frequencies of expectation:

$$E(r) = T\, p(r)$$

These predicted or expected numbers of sub-areas can be used together with the observed numbers of sub-areas in a chi^2 test, to determine if rock glaciers are distributed at random. The test statistic has C - 2 degrees of freedom, where C is the number of categories (8). One degree of freedom is lost because the expected frequencies are constrained to sum to 51, and another degree of freedom is required for the estimation of the mean (λ). For a degree of freedom of 5, the null hypothesis can be rejected at the 10% significance level (critical value = 9.24, chi^2 = 32.1126). The statistical test well exceeds the significance level, so the hypothesis of equality between the observed and expected random distributions can be rejected.

The Poisson model is not appropriate to describe rock glacier distribution in the Argentera Massif.

TABLE 2 - Poisson analysis. Poisson calculation for probability of event r_i per subarea, expected frequency and observed frequency of subareas with r_i events. Expected frequency was constained to sum of 51

N° rock glac. per subarea	Poisson equation	Poisson probability	N° subareas expected	observed
0	$e^{-1.39}\ \frac{1.39^0}{0!}$	0.249	12.72	21
1	$e^{-1.39}\ \frac{1.39^1}{1!}$	0.346	17.68	11
2	$e^{-1.39}\ \frac{1.39^2}{2!}$	0.240	12.26	9
3	$e^{-1.39}\ \frac{1.39^3}{3!}$	0.111	5.674	5
4	$e^{-1.39}\ \frac{1.39^4}{4!}$	0.038	1.942	2
5	$e^{-1.39}\ \frac{1.39^5}{5!}$	0.010	0.511	1
6	$e^{-1.39}\ \frac{1.39^6}{6!}$	$2.4 \cdot 10^{-3}$	0.122	1
7	$e^{-1.39}\ \frac{1.39^7}{7!}$	$4.9 \cdot 10^{-4}$	0.024	0
8	$e^{-1.39}\ \frac{1.39^8}{8!}$	$8.6 \cdot 10^{-5}$	$4.39 \cdot 10^{-3}$	1
			tot. 51	tot. 51

Testing cluster distribution - In a Poisson-type distribution the variance must be equal to the mean (random pattern). Mean value (λ) greater than the variance indicate a pattern more uniform than random, while mean value lower than variance can be referred to a pattern that is more clustered than random (Davis, 1986).

The variance (δ^2) in number of events (r) (rock glaciers) per sub-areas is:

$$\delta^2 = \Sigma_{i=1}^{N} (r_i - \lambda)^2/T - 1$$

Some differences between δ^2 and mean values can be attributed to the shape of the sub-areas chosen. The standard error of the mean value of the rock glaciers per subarea is:

$$Se = \sqrt{2/(T-1)} = 0.2$$

The t test compares the ratio between λ e δ^2, which should be equal to 1 if the statistic were the same (random pattern):

$$t = (\lambda/\delta^2) - 1.0/Se$$

The t statistic for the test of equivalence of the mean and variance is - 2.64. At a significance level of 10% and 50 degrees of freedom, the critical value of t for the two-tailed test is between ± 1.684 and ± 1.671. The test statistic exceeds this value, so the hypothesis of equality between the observed and expected distribution must be rejected and it can be concluded again that the Poisson model is not appropriate. Furthermore, since the variance is greater than the mean, it could be concluded that the rock glacier distribution is quite areally clustered.

DISCUSSION AND CONCLUSION

The distribution of the rock glaciers on the Italian side of the Argentera Massif is weakly irregular and is clustered. Fig. 1 shows clearly the presence of rock glaciers continuously along the axial chain, with the exception of a gap corresponding to the most southerly part of the alpine watershed (Gelas, Maledia and Clapier sectors). Also the distribution in the internal part of the main chain shows an area almost totally without rock glaciers (Argentera sector).

The main parameters that regulate the formation and creeping of mountain permafrost are the mean annual air temperature and the amounts of snow precipitation. Parameters that are determinant, but not sufficient, are availability of detritus and slope gradients steep enough to generate the permafrost creeping.

Given the homogeneity of lithology and fracturing of the crystalline rocks, in general the availability of detritus can be considered equal in all the sub-areas of fig. 1. The presence of a sufficiently high area of relief allows the recording at different altitudes of various generations of rock glaciers, as a consequence of the variation of the position of the isotherm –1 °C. Therefore the density of the rock glaciers can be directly proportional to the extension of the relief on which they develop.

The highest relief forms of the study area are (obviously) arranged along the main chain (alpine watershed), but also along an internal orographic alignment with respect to the chain axis, where there are also the highest summits of the area (Cima Argentera, Mt. Matto). In this sense we can explain the maxima of density of rock glaciers along the axial chain, but also along this internal belt of relief which from Rocca dell'Abisso extends as far as Mt. Matto, recently interpreted from a geodynamic point of view (Ribolini, in press). However, the distribution of the frequencies along these belt is not continuous, with areas lacking in, or almost completely without, rock glaciers (Gelas-Maledia-Clapier sector, Argentera sector) (fig. 1).

The rock glaciers of the Argentera Massif often show clear relations with the glacial deposits. The passage from glacial to periglacial conditions has generated a series of transitional landforms. In the upper part of the slopes and inside the cirques there are: a) glacial deposits that have evolved due to permafrost creeping b) rock glaciers that have moved overlapping the back sides of moraines, making it difficult to distinguish the landform (Ribolini, 1997b). In addition, various rock glaciers are made up of various main lobes, as a consequence of polyphase reactivation. The first case, which is more frequent, indicates a gradual transition from the glacial to the periglacial environment, which must have co-existed only for a certain time. The second case indicates the presence of one or more periglacial phases equivalent to those which, in other sectors of Argentera, were phases of glacial advance.

The discordance between potential of development and lack of rock glaciers in the sectors of the Gelas-Maledia-Clapier and of Argentera can be due to the timing of the deglaciation. In these areas the glacial environment persisted longer before being substituted by perigla-

cial conditions, as shown by a glacialism which have only recently become extinct (Argentera sector) or which are currently still in act (Clapier-Maledia-Gelas sector) (Federici & Pappalardo, 1996). The areas of relief outside of these sectors and at the same altitudes have been able to develop more generations of rock glaciers, periglacial conditions having been verified in all the high parts of the slopes. The altimetric distribution of the heights of the fronts is quite continuous (from 2.400 to 2.600 m) for the rock glaciers along the main chain and at the SW and NW borders of the study area. The fronts of the rock glaciers in the recently deglaciated sectors are at altitudes higher than 2.570 m.

The analysis of the areal distribution of the rock glaciers can therefore be considered a tool to understand, in a preliminary phase, the general model of deglaciation of an area. The study of relations between glacial deposits and rock glaciers, currently in progress in the Argentera Massif, can indirectly give more precise information on the evolution of recent glacial phases.

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