Geodesic and Photogrammetric Techniques for the Cartographic Production and the Observation of the Geomorphic Dynamic of the "Corral del Veleta" Active Rock Glacier (Sierra Nevada - Spain)

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Abstract

The southern most active rock glacier in Europe and the highest peaks in the Iberian Peninsula can be found in Sierra Nevada. The "Corral del Veleta" rock glacier can be found in the interior of the old cirque glacier that borders, with a northern orientation, at the base of "Veleta" peak (3,398 m a.s.l.). This rock glacier exhibits dimensional redundancies: 120 m longitude, 3,700 m² of surface area, its front is situated at an altitude of 3,090 m a.s.l. The study of this rock glacier is especially interesting because of its meridional location in the European context (37° N) and for its proven rapid morphodynamic response to the current environmental conditions (thermic and snow). The temperature of the surface of the ground in the summer months (July and August) can reach 27°C and the annual thermic amplitude 43°C.

At present, two main types of geomatic analysis are being carried out on the rock glacier: the production of detailed cartography and the observation of the geomorphic dynamic (displacement, sinking). Since 1995, geomatic observations have been carried out; although with a constant and systematic character only since 2001 (six campaigns). In order to perform this analysis, geomatic techniques have been employed: terrestrial photogrammetrics (photogrammetric camera), classic geodesy (total station) and Global Positioning System (GPS-RTK):

1. Cartographic production of the rock glacier: The technique employed to obtain the detailed cartography was photogrammetrics, with maps at a scale of 1/1000, and equidistance of the curves of 1 m have been generated.
2. Observation of the rock glacier dynamic: The classic geodesy and GPS were employed in the calculation of the glacier dynamic. Marks on large boulders and 35 rods located on the rock glacier are controlled.

The future geomatic study of the "Corral del Veleta" rock glacier is focused on two lines of investigation:

1. Determination of the movement of the rock glacier in the winter period (existence of snow cover) and its dynamic in the summer period (snow cover is nonexistent and the environmental temperature is elevated).
2. Search for a mathematical formula that relates the rock glacier dynamic to the climatic conditions (temperature, snow cover). But to do this, the availability of greater periods of field observation would be necessary.

KEY WORDS: "Corral del Veleta" rock glacier, Sierra Nevada, geodesy, global positioning system, photogrammetry, temperature

1. Introduction and geographical setting

During the "Little Ice Age" (from the 15th century to the 19th century) the source of the Guarnón ravine (northwest façade of the Sierra Nevada, SE Iberian Peninsula) housed a small glacier in the redoubt of Corral del Veleta. Its recent disappearance has been substituted by the development of different morphogenic cold processes and new modelling forms of a periglacier character. Of these, the prolonged detritus slope located in the transition of the rock wall of the Corral and its adjacent hollow stand out. The slope exhibits different levels of instability according to its sectors. It appears very active in its central and eastern sector where the weathering processes (cryoclasty) and evacuation (cryoreptation, gelifluction and flows) are more effective because of the existence of deep beds of permafrost in the slope. This explains the wide variety of the modelled forms (Gómez et al. 2003).

Of the groups of forms which have their origins in the detritus slope, a small rock glacier stands out. It is housed in the vicinity of the Corral del Veleta lagoon (3,080 m) and set on ice masses and beds of permafrost (Fig. 1). Its origin, which is still unclear, could correspond to a temporal evolution of both simple and complex forms that probably began around the second half of the 20th century (Gómez et al. 2003).

In 1995, when the Corral del Veleta was clear of snow, its morphology was analyzed for the first time and its geomorphological cartography was done in detail. Also, the hypothesis of the dynamics of its shapes, specially that of the rocks glacier (mentioning its possible settling on the frozen mass) was questioned. This last fact was proved in 1998 by using geophysical procedures and by extracting samples (Gómez et al. 1999, Gómez et al. 2001). It was found out that the frozen block trapped under the clastic layer remained 1.90 m below the surface. Looking at the results, from then on there has been a study on the morphological repercussions of the physical evolution of the active layer in the group of shapes of the Corral del Veleta (Gómez et al. 2004a).

This time the article deals with the control of the motion of the rocks glacier (displacement and sinking) through the checking of the metallic rods installed on the surface. The techniques that have been used are:

a) Classical topography with high precision total station.

b) Global Positioning System.

c) Mapping with close-range photogrammetry.

Figure 1: Photograph of the "Corral del Veleta" rock glacier (July, 2006) and the "Veleta" peak.

2. Geomatic techniques applied to the study of the "Corral del Veleta" rock glacier

Geomatic techniques (geodesy, GPS and photogrammetry) applied to the study of Corral del Veleta rock glacier have focused in two directions:

- Techniques applied to the securing of detailed cartography: In order to represent forms (grooves, arches,...) of the rock glacier, it is necessary to have a wide variety of information (photographs) available. For this reason, we can look for cartographic representations by means of photogrammetric techniques. The precision of photogrammetry is worse than that obtained by geodesic techniques or GPS, given that you depend on the coordinates supplied by the latter to determine the positions of the "control points" and to this error, we must add those typical to photogrammetric restitution.
- Techniques applied to the precise determination of the dynamic: Active rock glaciers are displaced very slowly and their dynamics are not equal over the whole surface (for example: the frontal-central zone has a higher dynamic) and for this reason more precise techniques (geodesy and GPS) should be used, where stable elements (rods) are seen to be located on the rock glacier.

While geodesy and GPS are used every year to calculate displacement (direction and magnitude) of the glacier, photogrammetry is only used in five year periods to compare morphological variations of the glacier.

2.1. Geodesy

Using classic geodesy (theodolite precision, total station) angular observation and distanciometrics can be made. In order to achieve this it is necessary to use observation stations, reference signs and aiming elements.

For the auscultations of precision, as in our case it is necessary to use high quality instruments (telescopic amplification, sensitivity of levels, angular value and error in distance). With respect to the angular value, instruments should be used with angular measurements of the limbs (horizontal and vertical) equal to or less than 10cc and with error in distance equal to or less than 2 mm ± 2 ppm (Sanjosé et al. 2004).

Both in the angular measurements and in the distances there should be an abundance of information in order to obtain statistical data. The coordinates of the rods are determined by using topographical computer programs. When the calculations of the position of the rods are made with several observations spaced out over time, the direction and magnitude of the displacement in each rod can be calculated by the increase in coordinates.

2.2. Global Positioning System

Global Positioning System is based on a minimum constellation of 24 active artificial satellites, but the minimum imposition of four satellites is necessary in order to calculate the position of the receptor, given that the four unknown values are coordinates of the point (X,Y,Z) and time (t). The value of the precision in the calculation of the position of the receptor will depend on the geometry the satellites form (the acceptable values of the GDOP are between 1 and 8) (Sanjosé et al. 2004).

The satellite technique employed in the study of rock glaciers has been "differential" positioning, which consists of at least two receptors simultaneously measuring a determined base-line (vector that connects the position of the receptors). With this method of operation a large part of the errors that affect one of the receptors also affect equally the other receptor. If you look at the coordinates of one of them above a point of known coordinates (reference station) you can calculate the position of the second receptor with respect to the first with great relative exactness (although absolute exactness will be of metric order). Therefore, the corrections that are applied to each of the determined distances to the satellites in the fixed receptor will be the same corrections to apply to the mobile receptor.

The processing of the information can be done in real time using the transmission of the correction by radio-modem (RTK) or in the post processing once the data has been taken. If the post processing technique offers greater precision (millimeters), the time of observation for each point should be greater and there is no guarantee of the resolution of ambiguity. On the other hand, using RTK, you obtain an instantaneous visualization of the results and the estimated exactness is known a priori at each point. Using RTK, the exactness obtained is in ± 3 cm for the horizontal component and ± 4 cm in the vertical.

2.3. Photogrammetry

In order to apply the photogrammetric technique, at least two different photographs of the same object are necessary. With the photogrammetric technique it is possible to transform bi-dimensional photographic information into tri-dimensional (X,Y,Z) information of the photographed object.

The photographs can be aerial or terrestrial, based on the positions of the point of shooting. That is, if the photographs are taken from an airplane with a photogrammetric camera, then we are speaking of aerial photogrammetry. But, if the photographs are made from a stable site (i.e. a tripod) located on the ground, then we are dealing with terrestrial photogrammetry (Sanjosé et al. 2004).

Geometric differences exist between the aerial photographs and the terrestrial photographs. In other words, while the aerial photographs have a geometry that is, in general "normal" with recoverings of 60% and errors of verticality of the shots inferior to 3g, in terrestrial photogrammetry the geometry of the shots would be: "normal" using bi-cameras, "inclined" and "convergent".

For the concrete study of rock glaciers, terrestrial photogrammetry has been used for the economic savings of not using an airplane for flight photogrammetry. On the other hand, analytical or digital stereoplotters can also be used (Kaufmann, 2000, Kääb 2000). For cartographic production of the "Corral del Veleta" rock glacier, by means of normal shots, analytical (vectorial) restitution has been employed.

3. Mapping of the "Corral del Veleta" rock glacier

For the cartographic production of the "Corral del Veleta" rock glacier, photographs were taken from the "Veleta" peak. This peak has an "almost" vertical cut with respect to the glacier; therefore we tried to take the photographs parallel and perpendicular to the photogrammetric base.

In this case, a high quality analytic restorer (SD 2000, Leica) was used for the photogrammetric restitution. In order to obtain the absolute orientation of the "control points", coordinates geodesic techniques and GPS were used (equal to the calculation of the glacier dynamic). The photogrammetric orientation process has a final error of

15 cm in the absolute orientation and a geomorphic map with a scale of 1/1000 (Fig. 2).

Presently, for map production of geomorphic structures (dunes, glaciers,...) where the photographic shots are not normal, that is convergent and inclined, a program called "Fotocartógrafo" is being implemented which performs this process automatically and allows for the acquisition of a great number of points. (López et al. 2005).

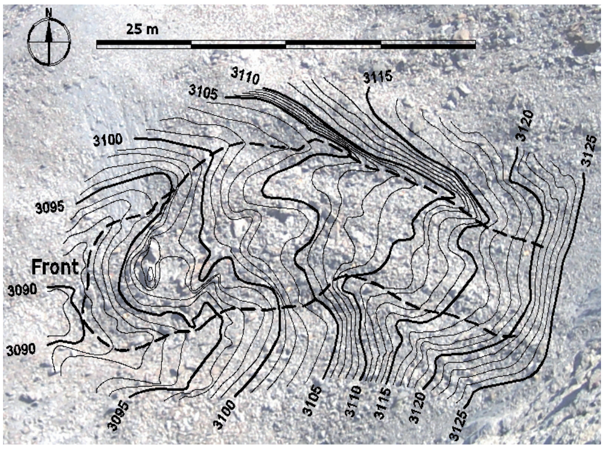

Figure 2: Cartography of the "Corral del Veleta" rock glacier to scale 1/1000.

4. Dynamic of the "Corral del Veleta" rock glacier

Between the years 2001 and 2006 geodesic and satellite campaigns were carried out on the "Corral del Veleta" rock glacier. The only observation station has been located on the inactive moraine lateral of the glacier. In 2001 14 rods (rock glacier, muddy outflow) were placed and later in 2002, another 21 rods were added. In Fig. 3, only the rods located on the rock glacier are represented and they were measured for five (2001 - 2005) years (Tab. 1). All the observations were carried out between August 29 and September 2. This year, the sixth observation was performed on August 29 and it is now in the process of being calculated.

The geodesic observations are realized with a total station and the same points are measured with GPS. The geodesic observations with GPS have two independent series, so that the difference of coordinates among them is less than 3 cm. This result of the total station coordinates was compared with the GPS coordinates, and their differences are less than the 3 cm tolerance in planimetry and 4 cm in altimetry.

When a "series" of data was finalized and the results of the GPS showed values superior 4 cm in a particular rod, we went on to perform the process of "reoccupation". This difference in results (generally exaggerated) could be attributed to the "multipath" effect when the satellite signal bounces off the walls of the glacier.

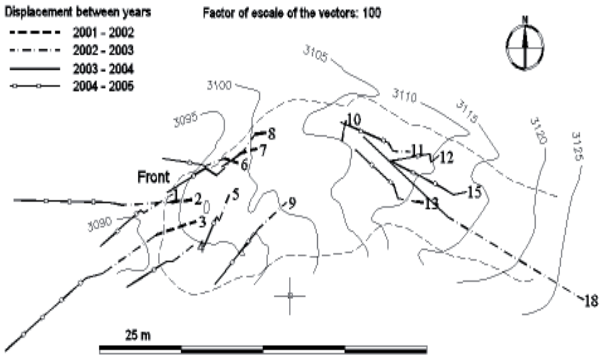

Figure 3: Dynamic of the "Corral del Veleta" rock glacier (2001 – 2005).

	Difference 2002 - 2001			Difference 2003 - 2002			Difference 2004 - 2003			Difference 2005 - 2004		
Point	Angle	Distance	Z	Angle	Distance	Z	Angle	Distance	Z	Angle	Distance	Z
1				168,308	0,105	-0,313	236,079	0,013	-0,072	159,033	0,160	-0,632
2	194,049	0,064	-0,246	196,759	0,157	-0,384	210,273	0,044	-0,115	201,265	0,302	-0,654
3	182,086	0,133	-0,150	165,596	0,198	-0,382	185,825	0,054	-0,146	158,994	0,321	-0,749
4				163,728	0,076	-0,341	200,000	0,020	-0,077	168,105	0,144	-0,887
5				127,645	0,076	-0,287	259,969	0,014	-0,067	130,150	0,090	-0,522
6	216,950	0,045	-0,125	179,830	0,064	-0,299	220,483	0,013	-0,071	208,235	0,124	-0,515
7	186,079	0,055	-0,242	157,150	0,095	-0,239	233,050	0,040	-0,090	168,647	0,140	-0,445
8	194,556	0,035	-0,142	143,987	0,067	-0,226	173,375	0,010	-0,070	167,325	0,063	-0,441
9				157,132	0,114	-0,324	150,000	0,018	-0,063	148,027	0,183	-0,700
10				118,555	0,031	-0,299	120,483	0,003	-0,087	105,522	0,023	-0,645
11				202,273	0,056	-0,328	261,904	0,027	-0,099	221,864	0,160	-0,865
12				163,135	0,031	-0,266	288,550	0,022	-0,072	190,397	0,126	-0,911
13	205,771	0,022	-0,181	209,637	0,060	-0,282	277,360	0,037	-0,099	241,542	0,155	-0,854
15				188,017	0,043	-0,188	231,445	0,044	-0,068	225,678	0,171	-0,968
18				229,927	0,486	-0,219	242,576	0,340	-0,140	236,257	0,465	-0,328

Table 1: Angle, distance of displacement (horizontal) and sinking (vertical) of some rods (2001 - 2005).

The most significant aspect of the dynamic behavior of this glacier is that its altimetric displacement (sinking) is greater that its planimetric displacement. This is due to its location prior to becoming a “fossil” glacier.

5. Relation between the glacier dynamic and the ambient temperature

The superficial changes and movements detected in the rock glacier (Fig. 3) during the observation periods offer evidence of its instability and the very close relation that such movements must maintain with even the smallest fraction of mechanical behaviour that make up the rock glacier. This is the basis for our proposal of the hypothesis that the immense frozen masses in the hollow of the rock glacier formed during the cold season melt in the summer and that the base in which this sedimentary body is set which corresponds to the ice masses and deep permafrost must be found at a certain degree of degradation. Both ideas could explain the planimetric movements (of advance) and the other vertical movements (sinking) (1). Since 2001 temperature registration of the rock glacier has been taken at different depths in order to obtain more information on these events. The most relevant information is summarized below (Gómez et al. 2004b):

1. There is a disproportion in the values given by rods located on the surface of the rock glacier (planimetric displacement-advance versus a vertical displacement-sinking) (Tab. 1).
2. The information also indicates that the active layer could have a thickness of greater than 90 cm, but not greater than 190 cm since from such depths temperatures are always negative although without reaching the zero annual amplitude (ZAA; Zero Annual Amplitude). Values at a depth of 40 cm from the surface are shown in Tab. 2.
3. The causes of the instability of the rock glacier’s surface, and based on the study hypothesis, should be subordinate, above all, to the temperature effect of the expansive wave of external radiation, which is at a maximum when the ground is devoid of snow (in summer, which can be nonexistent or irregular in thickness and covering) since this is when the softening temperature effect of the detritus mantle becomes annulled (Tab. 3).
4. The maximum values detected in the displacement of the rods should correspond at the end of summer (August-September) and also correspond to the accumulated sums from the moment in which the snow disappears from the ground. The observations carried out in July of the 2005-2006 periods appear to confirm this (Tab. 4).
5. The maximum planimetric displacements coincide with rods 1, 2, 3, and 4. This could be attributed to their location on the surface of the rock glacier which corresponds to the front sector of the greatest slope.
6. Our studies are currently focused on finding a mathematical formula (statistical) for each rod, in which the correspondence between the glacier dynamic and the temperature can be established. Once determined, the statistical formula could predict the expected displacement of each rod on the glacier for a given temperature

Period	Snow coverage rank	Movement average XY (cm)	Movement average Z (cm)
2001-2002	Partial	5,9	-18,1
2002-2003	Free	10,3	-27,3
2003-2004	Partial	4,3	-8,3
2004-2005	Free	16,4	-63,2

Table 3: Average referential values of the movement of the rods (cm) and the degree of covering (end of August).

Months	Temp.	Months	Temp.	Months	Temp.	Months	Temp.
September 2001	3,2	September 2002	4,9	September 2003	4,2	September 2004	6,8
October 2001	-2,5	October 2002	0,5	October 2003	0,2	October 2004	1,6
November 2001	-3,5	November 2002	-1,5	November 2003	-0,8	November 2004	-3,4
December 2001	-4,4	December 2002	-0,8	December 2003	-0,9	December 2004	-3,8
January 2002	-4,5	January 2003	-1,3	January 2004	-1,5	January 2005	-4,9
February 2002	-4,6	February 2003	-1,9	February 2004	-2,3	February 2005	-6,7
March 2002	-4,9	March 2003	-2,2	March 2004	-2,5	March 2005	-5,8
April 2002	-4,7	April 2003	-2,1	April 2004	-2,5	April 2005	-2,5
May 2002	-2,7	May 2003	-0,4	May 2004	-0,9	May 2005	1,3
June 2002	-2,7	June 2003	-0,2	June 2004	-0,1	June 2005	9,1
July 2002	4,5	July 2003	4,2	July 2004	-0,1	July 2005	13,4
August 2002	9,4	August 2003	11,2	August 2004	6,0	August 2005	11,9

Table 2: Temperature data by month (from September 2001 to August 2005) at a depth of 40 cm.

value. These predictions could be made even when the rock glacier ceases to be active.

	July 2006 - 2005		
Point	Angle	Distance	Z
1	113,438	0,043	-0,129
2	166,425	0,105	-0,240
3	140,877	0,144	-0,294
4	127,884	0,087	-0,288
5	97,454	0,050	-0,126
6	153,740	0,024	-0,151
7	165,595	0,058	-0,131
8	100,000	0,030	-0,108
9	111,337	0,051	-0,167
10	59,969	0,041	-0,173
11	207,917	0,008	-0,140
12	355,771	0,016	-0,107
13	20,483	0,025	-0,302
15	174,866	0,013	-0,164

Table 4: Angle, distance of displacement (horizontal) and sinking (vertical) of rods (July 2006 - 2005).

6. Conclusions

The morphodynamics which characterize the whole of the "Veleta" unit are typical of a recently deglacierized space that still houses in the hollow of "Corral del Veleta" pockets or sheets of ice fossil and permafrost which is more or less continuous at certain depths.

The study being carried out on the rock glacier using the development of geomatic techniques (geodesy, GPS and photogrammetry) is providing excellent results for the analysis of its dynamics. Specifically, photogrammetry of convergent and inclined shots is being employed to obtain detailed maps. Geodesy (total station) and GPS are used to calculate the dynamics. In all the cases the geodesic data is confirmed with GPS, resulting in very similar values in both cases (discrepancies under 3 cm in planimetry and 4 cm in altimetry).

With the numeric data obtained from the use of geomatic techniques it has been shown that the morphodynamics is minimal or null in the snow layer covering the ground of the rock glacier. However, when it disappears (summer period) it becomes very active, primarily in sinking movements. The temperature values registered are in agreement with these observations.

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