RESPONSE OF EUROPEAN ROCK GLACIERS TO CLIMATE CHANGE. A COMPARATIVE ANALYSIS OF DOESEN (AUSTRIAN ALPS), POSETS (CENTRAL PYRENEES) AND CORRAL DEL VELETA (SIERRA NEVADA) DURING 2001-2008 PERIOD.

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ABSTRACT

The study of periglacial geomorphology can inform us of climate changes taking place throughout the Quaternary. Its analysis in the present day indicates the influence of climate on them, and a continuous sequence of its behaviour may even be an indicator of the future development of the rock glacier analyzed. In this paper a comparison is made of three rock glaciers: Doesen (Austrian Alps), Posets (Central Pyrenees) and Corral del Veleta (Sierra Nevada). In these three glaciers annual measurements were taken of horizontal and vertical displacement from the installation in 2001 of monitoring points (nails and rods) to 2008. Geodesic data were not available for the glacier of Doesen in 2003, nor for the Posets glacier in 2002, 2003 and 2004. Soil temperature data from the Corral del Veleta rock glacier were available for all the years of the study period (2001-2008).

The geomorphological dynamic of each glacier was related to the soil temperature conditions of the summers between 2001 and 2008. Different dynamics were detected in the various rock glaciers, although their behaviour was homogeneous. Greater horizontal displacement was found in the Doesen glacier, less horizontal dynamism in the Posets glacier, and greater vertical dynamism, due to thinning, and less horizontal dynamism in the Corral del Veleta glacier. This paper studies the relationship between the summers with warmer soil temperature records and greater dynamism of the rock glaciers, although the geomorphological responses are varied in relation to environmental location and topoclimatic conditions.

Keywords: Rock glacier, climate change, soil temperatures, geodesy, periglacial environments.

1. INTRODUCTION AND OBJECTIVES

Rock glaciers are good indicators of present-day climate related to thermal conditions in polar and high mountain regions, and have been used for reconstructing palaeoclimate and landscape evolution. In the late eighties just a dozen or so studies had been conducted on rock glacier dynamics. Two decades on, over a hundred detailed studies have now been made on rock glaciers in many mountain ranges around the world (Rocky Mountains, Alaska Range, Alpes, Pyrenees, Sierra Nevada, Scandinavian ranges, Andes, Antarctica, Himalayas or Tien Shan). Regional studies (distribution, inventory, statistical analysis, descriptives), local studies (geoindicators, geotechnical) or studies on structure and dynamic have led to the current exhaustive knowledge of these landforms.

In this study we discuss and compare the results obtained in three rock glaciers (Doesen, Posets and Corral del Veleta) located in the three highest mountain systems in Western Europe: Austrian Alps, Central Pyrenees and Sierra Nevada respectively. Dynamic data are available of the Doesen rock glacier from 1995 (Kaufmann et al., 2006), but not until 2001 were the first observations made of the other two glaciers (Posets and Corral del Veleta). The latter date is therefore taken as the origin of these comparisons. Thermal column data was only recorded in the Corral del Veleta rock glacier, and so only these data were available for application to all three glaciers.

The aim of this paper is to compare the dynamic (planimetry and altimetry) of each of the rock glaciers (Doesen, Posets, Corral del Veleta) with the thermal column information obtained, in this case in the Corral del Veleta. Evidently, more such data is needed from the rock glaciers of Doesen and Posets, but faced with this lack of information, an attempt was made to find any possible correlation among the three glaciers using the thermal column records from one glacier (Corral del Veleta) and extrapolating them to the others (Doesen and Posets).

2. GEOGRAPHICAL FRAMEWORK

2. 1. Doesen rock glacier (Austrian Alps)

The geographical coordinates of the Doesen rock glacier are 46º59´12´´ N;

13º17´08´´ E. It is found at between 2339 m (front) and 2650 m (root) and is 1000 m in length by 150 to 300 m wide. Its tongue is oriented west-east and its front slopes at around 40º. It is located in the Ankogel massif, in the Hohe Tauern National Park in Austria (Fig. 1).

Figure 1. General view of the Doesen rock glacier.

Researchers from the University of Graz carried out the studies on the Doesen rock glacier, and it was in 1990 that Professor Lieb (Institute of Geography and Regional Science of the University of Graz) began research into permafrost in Austria in the eastern area of the Austrian Alps. In his study, Lieb compiled 1450 rock glaciers in that area and drew up a geomorphological map (Lieb, 1996; Lieb, 1998).

Geophysical studies detected thicknesses of between 30 and 40 m, depending on the area. In 1995 the photogrammetric and geodesic studies commenced in order to obtain information on the glacial dynamic and to draw up the detailed geomorphological and topographical map. In order to determine the glacial dynamic by means of geodesic techniques, 34 points were placed on the surface of the glacier.

2. 2. Posets rock glacier (Central Pyrenees)

Posets rock glacier (42º39´32´´ N, 0º26´49´´ E) is located on the eastern slopes of the massif of the same name, in the Aragonese Pyrenees. The tongue develops at between 2995 m (front) and 3060 m (root) and faces northeast. It is a rocky glacial scouring, generated by a periglaciar dynamic and fed by debris from the Posets glacier (Fig. 2). It is currently disconnected from the debris source. The average width of the glacier is 200 m and the slope has four different areas: the root: 7º, the high area: 15º, the middle: 24º-30º and the front: 40º-45º.

Figure 2. General view of the Posets rock glacier.

The dark sedimentary formation located downstream of the Posets ice patch was interpreted as a rock glacier (Hamilton, 1988) and classified as a glaciogenic rock glacier (Serrano and Agudo, 1998; Serrano et al., 1999; Serrano et al., 2009), connected in the past to the Posets glacier. In the present-day the rock glacier is disconnected from walls and debris talus and has no debris nor ice supply from any wall or glacier.

Vertical electric sounding, BTS and ground thermal measurement, debris surface analysis and a DGPS survey were performed on this rock glacier between 1994 and 2008. High precision records of horizontal and vertical movements of the rock glacier were measured using a DGPS on ten steel rods from 2001.

2. 3. Corral del Veleta rock glacier (Sierra Nevada)

The Sierra Nevada is the highest massif in the Iberian Peninsula (Mulhacén, 3482 m). During the Quaternary glaciations and the Little Ice Age (XIV-XIX centuries) the southernmost glaciers of Europe developed in the high cirques of the mountain. The Corral del Veleta, a glacial cirque located on the north face of the Veleta peak (3398 m) at the top of the Guarnón valley, remained within a small glacier during the Little Ice Age until the middle of XX century (Fig. 3). In the present day the glacier no longer exists, but there is relic ice and permafrost, both in process of degradation (Gómez-Ortiz et al., 2001; Tanarro et al., 2001; Gómez-Ortiz et al., 2002; Gómez-Ortiz et al., 2003).

Figure 3. General view of the Corral del Veleta rock glacier.

The small rock glacier (37º03´33´´ N; 3º21´47´´ W) is an 'L' shape. It begins from the block flow attached to the wall of the Corral and extends in a northern direction progressing westerly, with lobes and coalescent arches, and filling the small basin between the cirque and the fontal moraines (Sanjosé et al., 2007).

In 2001, 27 rods of 1,25 m were installed on the rock glacier, and since then annual measurements have been taken.

3. METHODOLOGY

3. 1. Thermal column data

In 2001 a thermometer column was installed in the Corral del Veleta rock glacier. The depths of the thermal sensors installed were -15 cm, -40 cm and -90 cm. Table 1 shows the mean values recorded (ºC) in May, June, July and August (in May the ground snow begins to melt, a process which lasts until the end of August and from September temperatures tend to fall, gradually increasing the likelihood of snowfall), and the number of days with temperatures above 0 ºC and of those above 10 ºC. The values, as a whole, reveal the progression over time of the thermal radiation wave in the ground.

One of the aims of this study was to extrapolate the thermal column data obtained in the Corral del Veleta (Table 1) with the dynamic of the three rocks glaciers. Evidently, these thermal column data must coincide with the dynamic of the Corral del Veleta rock glacier, but would there be any correlation with the rock glaciers of Doesen and Posets?. In order to analyze the responses to climate changes, we needed the thermal column data from meteorological stations near to each of the Doesen and Posets, but these data were not available, so we searched for a possible relationship between the thermal column data obtained in Corral del Veleta and the others glaciers.

Annual period	2001 - 2002			2002 - 2003			2003 - 2004			2004 - 2005			2005 - 2006			2006 - 2007		
Depth (cm)	-15	-40	-90	-15	-40	-90	-15	-40	-90	-15	-40	-90	-20	-50	-100	-20	-50	-100
May (ºC)	-2,4	-2,7	*n. d.*	*n. d.*	-0,4	-0,3	-0,9	*n. d.*	-1,3	1,3	*n. d.*	0,6	-0,1	-0,2	*n. d.*	-0,9	-1,0	*n. d.*
June (ºC)	-2,3	-2,7	*n. d.*	*n. d.*	-0,2	-0,1	-0,1	*n. d.*	-0,3	9,1	*n. d.*	5,9	3,1	2,4	*n. d.*	0,1	-0,1	*n. d.*
July (ºC)	6,5	4,5	*n. d.*	*n. d.*	4,2	2,4	-0,1	*n. d.*	-0,3	13,4	*n. d.*	9,2	12,0	10,1	*n. d.*	10,5	8,3	*n. d.*
August (ºC)	11,5	9,4	*n. d.*	*n. d.*	11,2	8,1	6,0	*n. d.*	3,7	11,9	*n. d.*	8,6	10,7	9,5	*n. d.*	11,3	10,0	*n. d.*
Number days > 0 ºC	51	50	*n. d.*	*n. d.*	49	50	25	*n. d.*	25	105	*n. d.*	105	84	83	*n. d.*	68	67	*n. d.*
Number days > 10 ºC	34	27	*n. d.*	*n. d.*	32	0	7	*n. d.*	0	69	*n. d.*	10	52	22	*n. d.*	30	27	*n. d.*
Qualitative value	MODERATED			MODERATED			COLD			WARM			MODERATED HIGH			MODERATED DOWN		

n. d.: no data (error in the thermometer measurement).

Table 1. Mean monthly temperature at different depths, number of days a year with positive mean temperature (0 ºC and 10 ºC) from 2001 to 2007 and qualitative classification in summer.

In 2008, following the model of Corral del Veleta, thermometers were placed in the area of the Posets-Maladeta Natural Park and that same year geodesic and thermal measurements began of the Maladeta rock glacier (37º03´33´´ N; 3º21´47´´ W), to the north of the Alba glacier and near the Posets rock glacier. Similarly, in the area of influence of the Doesen rock glacier thermometers were also placed, as part of the Alpchange project "Climate Change and Impacts in Southern Austrian Alpine Regions".

Moreover, since 2006 two geodesic measurements are taken yearly (at the end of July and end of August) on the Corral del Veleta rock glacier, in order to know the thermal influence of August on the glacial dynamic.

3. 2. Geodesic monitoring

Geodesic monitoring consisted of measuring the horizontal and vertical displacement of the rock glacier. It was performed by monitoring fixed points: metallic rods on the debris and nail installed on the surface of blocks located on the rock glacier.

Data collection was made using Total Station or Differential Global Positioning System (DGPS) from stable stations outside the rock glacier. The values of displacement of the signals located in the rock glacier had a margin of error of ± 3 cm. For a single survey, the observations with Total Station have two independent series, the difference in the coordinates for a single signal between the two series being of less than 3 cm. If the observation is made with DGPS, the positioning error shown on the screen of the mobile receptor must be less than 3 cm, but when this is not so, once a measurement is ended the process of 'reoccupation' begins, i.e. the point is measured once more (Sanjosé et al., 2004).

4. RESULTS

The results of the dynamic of each monitoring point are published in different papers (Doesen, Posets and Corral del Veleta) (Kaufmann et al., 2006; Serrano et al., 2009; Gómez-Ortiz et al., 2008). The horizontal and vertical displacements of the front, center and root of each rock glacier are described below (Table 2, 3 and 4).

4. 1. Doesen rock glacier (periods 2001-2002 and 2004-2008)

Geodesic recording instruments were installed on the glacier in 1995. Seven reference stations and 34 monitoring points were set up on the rock glacier. In addition to the measurement of these 34 points, two longitudinal and two transversal profiles were also monitored, such that a total of 75 points were measured in the profiles (Kienast and Kaufmann, 2004; Kaufmann et al., 2006).

POINTS	2001-2002	2002-2004	2004-2005	2005-2006	2006-2007	2007-2008
Front (5,7,8)	26.6 / -6.3	29.0 / -6.3	26.5 / -4.5	19.3 / -2.1	20.6 / -4.5	19.5 / -4.2
Centre (14,15,16,21,22)	30.8 / -11.1	38.9 / -13.2	36.5 / -12.6	31.9 / -8.8	30.0 / -9.2	29.7 / -10.9
Root (32,34)	16.0 / -12.2	24.2 / -15.8	20.5 / -11.6	18.1 / -9.9	20.1 / -13.6	15.1 / -11.9

Table 2. Doesen: Mean horizontal / vertical displacement (by area) with values in cm.

The results shown in Table 2 for the Doesen rock glacier indicate that:

- In the bi-annual period from 2002-2004 the dynamic was lesser than in the previous (2001-2002) and following (2004-2005) annual periods. We pose the question, might it have been due to the fact that the 2003-2004 period was cold (conclusion obtained from the the thermal column data from Corral del Veleta), leading to a possible lessening of the glacial dynamic?.

- The Doesen glacier showed a greater horizontal than vertical dynamic and it was the central area of the rock glacier that registered greater horizontal movements. The central and root areas behaved similarly in vertical movement (Fig. 4).
- In general, this is a rock glacier with very stable behaviour and a homogeneous response every year. Therefore, can the thermal effect be interpreted as a relatively small one in comparison with more southerly European rock glaciers?.

4. 2. Posets rock glacier (2001 and the 2005-2008 period)

The data were collected from the ten monitoring points using bi-frequency DGPS equipment interconnected by radio-modem. To test the quality of the results, the reoccupation technique (monitoring the same point under different conditions) was used and precisions of 2-4 cm in X,Y,Z were obtained. The years observed were 2001, 2005, 2006, 2007 and 2008 (Serrano et al., 2009).

POINTS	2001-2005	2005-2006	2006-2007	2007-2008
Front (2,4,6)	43.9 / -27.3	7.6 / -10.0	11.3 / -12.2	6.9 / -3.7
Centre (5,7,10)	40.8 / -18.8	8.0 / -10.5	12.7 / -9.2	7.2 / -4.3
Root (8,9)	36.5 / -32.7	7.5 / -12.5	13.7 / -17.7	7.9 / -5.2

Table 3. Posets: Mean horizontal / vertical displacement (by area) with values in cm.

Table 3 shows the following results:

- For the 2001-2005 period there is insufficient information for any coherent conclusions to be drawn.
- As a whole, there was a greater horizontal than vertical dynamic, but with less clear values than in the Doesen rock glacier (Fig. 4). In some periods (2005-2006 and 2006-2007) there was even greater vertical than horizontal displacement.
- The values of the glacial dynamic were very similar in the whole rock glacier, with highly homogeneous displacement throughout (front, centre and root).
- In general, the dynamic of this rock glacier expressed marginal functioning, with moderate and differentiated flows, which characterize the periglacial processes of the Pyrennean high mountain. Its behaviour is similar to that of other rock glaciers of the Central Pyrenees, such as, for example, the Argualas rock glacier (Sanjosé, 2003; Serrano et al., 2006).

4. 3. Corral del Veleta rock glacier (2001-2008 period)

The geodesic observations on the Corral del Veleta rock glacier were made simultaneously using Total Station and DGPS. In some years the DGPS observation did not give good results owing to poor configuration of the satellites at the time of data collection. The Total Station data alone were used for these years and the DGPS data were omitted.

With the passing of time new monitoring points (rods) on the glacier were added and other rods disappeared, mainly in the rock glacier root, where there is a greater dynamic (Table 4).

POINTS	2001-2002	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008
Front (2,3,6)	8.0 / -17.3	13.9 / -35.5	3.7 / -11.0	24.9 / -63.9	18.6 / -46.6	19.5 / -47.00	11.7 / -43.5
Centre (10,11,12,13)	2.2 / -18.1	4.5 / -29.4	2.1 / -8.9	11.6 / -81.8	5.7 / -46.6	13.5 / -41.8	5.6 / -37.9
Root (20,21)	40.7 / -63.2	39.4 / -63.6	21.5 / -35.6	60.8 / -97.3	40.2 / -71.8	46.2 / -57.6	36.0 / -64.8

Table 4. Corral del Veleta: Mean horizontal / vertical displacement (by area) with values in cm.

Lastly, the results of the dynamic of the Corral del Veleta rock glacier, shown in Table 4, can be compared with the thermal column data (Table 1), and the conclusions that might be drawn are as follows:

- The root of the rock glacier did not behave homogeneously with the rest of the glacier, due to the steep slope forming a confluence with the wall of the glacial cirque. It is such an active area that rods commonly disappeared.
- The remainder of the glacier (front and centre) in milder years (2001-2002 and 2002-2003) had a dynamic similar to and greater than that of the cold year (2003-2004). Also, the dynamic was lesser in the 2001-2002 and 2002-2003 periods than in 2004-2005, 2005-2006 and 2006-2007. 2004-2005 was the most dynamic year, coinciding with the highest thermal values.
- The central area had the lowest horizontal dynamic, but the warmest year (2004-2005) saw the greatest degree of thinning. In the remaining years the central part behaved similarly to the front.
- Lastly, the most significant dynamic behaviour of the Corral del Veleta rock glacier was its greater displacement in altimetry (thinning), than horizontal displacement. Normally, in any rock glacier the dynamic is greater in the horizontal than in the vertical plane. This particular case arises because it is in a state prior to conversion to an 'inactive' rock glacier (Fig. 4).

5. INTERPRETATION OF THE RESULTS AND DISCUSSION

In the three rock glaciers analyzed some homogeneous and other contrasting behaviours were detected. The contrasting behaviours are the result of the differential periglacial processes and the different current climatic conditions. They are somewhat more similar between the Doesen and Posets rock glaciers, and there is more difference between those two and Corral del Veleta. The extent of the massifs they belong to and the latitude at which each is found are also determining factors.

The results show that between the three rock glaciers there are dynamic differences, but there is a common response. The Doesen rock glacier behaves very stably in that the thermal variations must have a relatively small influence in comparison with the other two rock glaciers. What they have in common is that they all present horizontal movement (in favour of the slope) and vertical movement (thining), which reflects their being active in spite of showing differentiated dynamics among them. The presence of a negative vertical movement (thinning) as sharp as in the case of Corral del Veleta is associated with the degradation of the frozen mass (relic glacial ice and permafrost) upon which the body of the rock glacier rests (Gómez-Ortiz et al., 2008). In the case of Posets and Doesen something similar may be happening, although the lack of thermal column data makes this impossible to confirm.

In Corral del Veleta the decisive role of the current climate was seen in the dynamic of the rock glacier, as the whole rock body is in a state of progressive deterioration. The information from the thermal column of the summers from 2001 to 2007 confirms these facts (Table 1), which are reflected, for example, in 2003-2004 and 2004-2005. In the summer of 2004 positive temperatures remained in the internal layers of the rock glacier to -90 cm for just 25 days. That same year the horizontal displacement of the centre of the rock glacier was 2,1 cm and its vertical displacement (thinning) was -8,9 cm. In the same period of the following year there were 105 days with positive temperature at the same depth; the centre of the rock glacier moved 11,6 cm and sank -81,8 cm. The reason for this unbalanced behaviour was the duration of the snow cover in the summer of 2004. Only in August was the rock glacier free of snow, whereas in 2005 the snow cover disappeared in May.

In the different dynamics of each glacier a common trend appears: the response of the rock glaciers to the warmest summers with greater dynamism. This response is greater in some glaciers, which respond with higher horizontal flow velocities (Doesen and Posets), than others, in which thinning increases, as in Posets to a certain extent, and in Corral del Veleta rather more clearly. We relate the relationship between warmer thermal ground conditions and greater dynamism to melting processes and water at the base of the frozen body, sometimes leading to an increase in deformation and flow, and at others to the melting of the frozen body with thinning and readjustment movements.

6. CONCLUSIONS

The comparative study of the three rock glaciers has allowed their dynamics to be described and a first contribution made to the knowledge of its behaviour and responses to climate changes. The rock glaciers present a common trend. Their most active dynamic coincides with the summers in which temperatures are warmer and there is a reduction in the snow cover, which facilitates the propagation of the thermal wave in the ground, as measured in Sierra Nevada.

The intrinsic characteristics of each rock glacier and their environmental location (latitude, extent of the massif, altitude, orientation, topoclimatic conditions, morphotopography, current climate) determine the dynamic of the glacier in terms of the values of displacement obtained (horizontal and vertical). These are at a maximum in Corral del Veleta (37º03´33´´ N), a deglaciated mountain with arid characteristics, whereas they are not so evident in Doesen (46º59´12´´ N), a mountain of mean latitude where quaternary glaciers still remain. In view of the results the Posets rock glacier (42º39´32´´ N), where remnants of small glaciers are still present, has an intermediate behaviour, though it is more similar to the Austrian Alps than Sierra Nevada (Fig. 4).

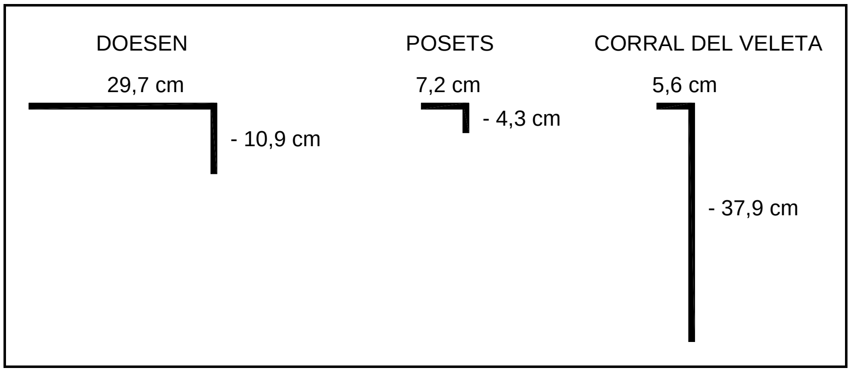

Figure 4. Horizontal and vertical (thinning) behaviour in 2007-2008 of mean displacements of the central areas of the Doesen, Posets and Corral del Veleta glaciers.

The different dynamic responses of the rock glaciers studied point out the sensitivity of these depositional bodies to environmental changes and their interest as geoindicators of environmental change in the high mountain. In this sense, this comparative study reveals a general trend that must be adjusted with more thermal information from rock glaciers (in particular Posets and Doesen) tested against the trends of the nearest stations. In this way we may obtain more detailed information on the climatic variations of each environment and know in greater detail the magnitude of the geomorphological responses.

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