Assessing the impact of Quaternary glaciations on the topography of Sierra de Gredos (central Spain)

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ABSTRACT

It is well known that glacial erosion modifies the topography by increasing the local relief, producing cirques and U-shaped valleys. During the Last Glacial Maximum (LGM) the glaciers that flowed down from the top of Sierra de Gredos, central Spain, modified the preexisting landscape forming cirques and causing the apparent deepening of valleys. Both, glacial advances and related landforms are well documented for Sierra de Gredos; however, quantitative estimates of how glacial erosion has modified the topography of the range have not been provided yet. We compare the means of relief, normalized steepness index (k_{sn}), and elevation of basins as well as the width, form ratio (F_R) and relief of ridge-to-ridge cross-sections of valleys to evaluate the impact of glacial erosion on the topography of the sierra. The idea that the relief production is high in fully glaciated basins contrasts with our results, which indicate that local relief is greater in the southern flank where glacial erosion was moderate and confined to cirques and where the rates of rock uplift are particularly high. Also, the maxima of local relief occur below the LGM equilibrium line of altitude (ELA). We postulate that in Sierra de Gredos, glacial erosion lowered the ridgelines and the bottom of valleys inhibiting the relief production. The high local relief on the southern flank is explained by the incision of bedrock rivers responding to high tectonic uplift rates. The glacial advances during the LGM may have increased the stream discharge, promoting the sediment evacuation and enhancing the bedrock incision.

Key words: relief, glacial erosion, basins, cross-sections, relief production, Sierra de Gredos, Spain.

RESUMEN

Es bien conocido que la erosión glacial modifica el relieve mediante el incremento del relieve local y donde se producen circos glaciales y valles con una morfología en "U". Durante el Último Máximo Glacial (UMG) los glaciares confinados a las partes altas de la sierra de Gredos (centro de España) modificaron el relieve mediante la formación de circos glaciales y la profundización de los valles. En la sierra de Gredos tanto los avances glaciales así como las formas resultantes están bien documentadas, sin embargo, no existe hasta el momento una estimación cuantitativa de cómo los procesos glaciales modificaron la topografía de la sierra. En este estudio comparamos los valores medios del desnivel, el índice normalizado de verticalidad (k_{sn}) y elevación de las cuencas así como la anchura, el valor fraccional de la forma (F_R) y el relieve local de las secciones de corte entre divisorias por cada valle con el fin de evaluar el impacto que tuvo la erosión glacial en la topografía de la sierra de Gredos. La idea de que la producción del relieve local es alto en las cuencas con alto grado de glaciarización contrasta con nuestros resultados, los cuales indican que el relieve local es mayor en el flanco sur de la Sierra de

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Gredos donde la erosión glacial estaba confinada a circos glaciales y donde las tasas de levantamiento tectónico son altas. También, los valores máximos del relieve local se localizan por debajo de la línea de equilibrio altitudinal. Nosotros sugerimos que la erosión glacial inhibió la producción del relieve local en la Sierra de Gredos debido a la erosión de las divisorias así como en el fondo de los valles. El incremento en la producción del relieve local en el flanco sur se explica por la respuesta incisiva de los ríos de lecho rocoso frente a las altas tasas de levantamiento tectónico. Es posible que los avances glaciales del Último Máximo Glacial incrementaran la descarga en los ríos, los cuales evacuaron una mayor cantidad de sedimentos y causaron una mayor incisión sobre el sustrato geológico.

Palabras clave: relieve local, erosión glacial, cuencas, secciones, producción del relieve, Sierra de Gredos, España central.

INTRODUCTION

The dissection of mountainous landscapes results from the interplay between tectonics and climate in which erosion dictates the rate of bedrock exhumation and lowers the elevation of mountain ranges (England and Molnar, 1990). Tectonics, via rock uplift, brings Earth's surface to high elevations providing the potential for it to be eroded and for relief to be produced by both glacial and fluvial processes (Whipple *et al.*, 1999). The duration and intensity of these processes are determined by climate (Anderson and Anderson, 2010). The debate about whether glacial erosion produces greater relief than fluvial incision still continues (*e.g.*, Harbor and Warburton, 1993; Whipple *et al.*, 1999; Montgomery 2002; Van der Beek and Bourbon, 2008; Amerson *et al.*, 2008).

Glacial erosion has been invoked as an effective mechanism capable of modifying the morphology of valleys (*e.g.*, Embleton and King, 1968; Graf, 1970; Harbor, 1992) and increasing the local relief (Montgomery, 2002). The U-shaped morphology, typical of glacial valleys, is regarded as unequivocal evidence of glacial erosion imprinted on the landscape (Harbor, 1992). The morphology of glacial valleys has been modeled using a power law function using the correlation between the elevation and length of valley flanks. In such power law function exponents > 2.0 are believed to reproduce the U-shaped morphology or alpine type morphology (*e.g.*, Graf, 1970; Hirano and Aniya, 1988). The exponent exhibit a positive correlation with ratio between the depth and width of a valley cross-section, known as the form ratio (F_R), where values exceeding 0.2 are common in glaciated valleys (Hirano and Aniya, 1988). Numerical and empirical data suggest, however, that U-shaped valleys can only be produced after ~500 ka of glaciation (Harbor, 1992; Brook *et al.*, 2006; Egholm *et al.*, 2009). Because glaciers require so long time to modify the morphology of valleys, it is possible that the development of U-shaped valleys is restricted to latitudes or altitudes where glacial erosion operates for long periods or where glacial erosion is particularly intense.

Variations in the extent of glaciations and the intensity of glacial erosion are expected from high latitudes towards the equator since the equilibrium line of altitude (ELA) and the glaciated surfaces depend on both altitude and latitude (Egholm *et al.*, 2009; Champagnac *et al.*, 2012). Depending on the extent of glaciations, it is likely that the local relief production as well as valley morphology change with altitude and latitude. Compiling the relief of several mountain ranges around the world, Champagnac *et al.* (2012) found that relief due to glacial erosion is found at high latitudes. Examples of glacial erosion resulting in high relief production rates have been reported for the Olympic Mountains, Washington (Montgomery, 2002), the Sawtooth Mountains, Idaho (Amerson *et al.*, 2008), Torngat Mountains (Canada) (Staiger *et al.*, 2005) and the western French Alps (van der Beek and Bourbon, 2008). In the Olympic Mountains and Sawtooth Mountains, glacial erosion has markedly increased the local relief in comparison to fluvial valleys where also the local relief of glacial valleys exhibits a correlation with the drainage area as it also occurs in fluvial valleys (Montgomery, 2002; Amerson *et al.*, 2008).

In other mountains settings, the relief production seems to be more limited as the observations for Sierra Nevada, California (Brocklehurst and Whipple, 2002) and the Rocky Mountains, Colorado (Anderson *et al.*, 2006b) indicate. Another important factor controlling the local relief production is basin size (Brocklehurst and Whipple, 2006). In some cases, glacial erosion seems to be particularly intense close or below the ELA, as recent numerical simulations suggest (Herman *et al.*, 2011). Moreover, observations in the glacial valleys of the Swiss Alps indicate that relief production increased below the ELA and postdates the onset of glaciations (Haeuselmann *et al.*, 2007; Valla *et al.*, 2011). In contrast, ice accumulation at the top of small basins may inhibit the relief production as reported for Sierra Nevada and Sangre de Cristo Mountains (Brocklehurst and Whipple, 2002, 2006) where the lowering of the crests of mountains prevent the increase of local relief (Brocklehurst and Whipple, 2006). A decrease in the relief production caused by the erosion of mountain crests is supported by the buzzsaw hypothesis (Brozovic *et al.*, 1997; Brocklehurst and Whipple, 2007; Egholm *et al.*, 2009) but whether this pattern applies for other glaciated mountainous settings needs to be confirmed.

A priori, it seems that glacial erosion can increase the local relief in: (1) settings where glaciations have covered large areas, (2) valleys where glaciers have flowed a long path (*e.g.*, Montgomery, 2002; Amerson *et al.*, 2008; Egholm *et al.*, 2009) and (3) areas covered by polythermal ice caps or sheets (Staiger *et al.*, 2005). In such conditions the erosion rates by glaciers increases with drainage area (Hallet *et al.*, 1996), thus the correlation between the local relief and drainage area is, in some way, expected (*e.g.*, Montgomery, 2002). In contrast, those settings where few areas lie above the ELA seem to have a different behavior because glaciers may be confined at the top of mountains (Anderson *et al.*, 2006a; Brocklehurst *et al.*, 2008; MacGregor *et al.*, 2009). Thus, variability in the relief production is likely to occur, presumably because of the basin size, the extent of high-elevated areas and the ability of glaciers to incise the bottom of valleys and ridgelines. The study of glaciated basins becomes necessary to understand how glacial erosion modifies those landscapes where few areas are above the ELA and to clarify whether local relief production is increased or inhibited.

We studied the basins of Sierra de Gredos (SG), located in central Spain because the need to evaluate the impact of glacial erosion on the mountain topography in areas above the Last Glacial Maximum (LGM) ELA. The study area presents an ideal opportunity to compare the increase in local relief of basins that exhibit clear marks of full glaciations with those that have had moderate glaciations or remain free of glaciers. Moreover, the tectonic control in this sierra allows exploring the role of rock uplift on the relief production. We compare the relief, elevation and normalized steepness index (k_{sn}) of basins and the relief, width and form ratio (F_R) of ridge-to-ridge cross-sections to provide quantitative estimates of the effects of glacial erosion imprinted on the topography of SG.

REGIONAL SETTING

Sierra de Gredos is a mountain range with peaks reaching an altitude of ~2200 to ~2590 m and forming a maximum range relief of ~2100 m (de Bruijne and Andriessen, 2002). The range is located in the western side of the Spanish Central System, an east-west structure crossing the center of the Iberian Peninsula (Figure 1). Rainfall in SG varies with altitude. The minimum annual rainfall in this range is ~500 mm at an altitude of ~1000 m, increasing to 2000 mm at ~2000 m; ~80 % of precipitation falls as snow (Palacios *et al.*, 2011). SG is constituted by granite of the Hercynian (late Paleozoic) crystalline basement (Tejero *et al.*, 2006). The granite of SG is, in non-glaciated areas, covered by a weathered mantle of ~ 4 to 5 m (Palacios *et al.*, 2012). The mountain range was fractured by Alpine Orogeny compressional stresses resulting from the Miocene convergence between the African and European plates, leaving a topography characterized by the development of normal and thrusting faults (Tejero *et al.*, 2006). The present-day topography of SG reflects the base-level lowering and drainage network re-

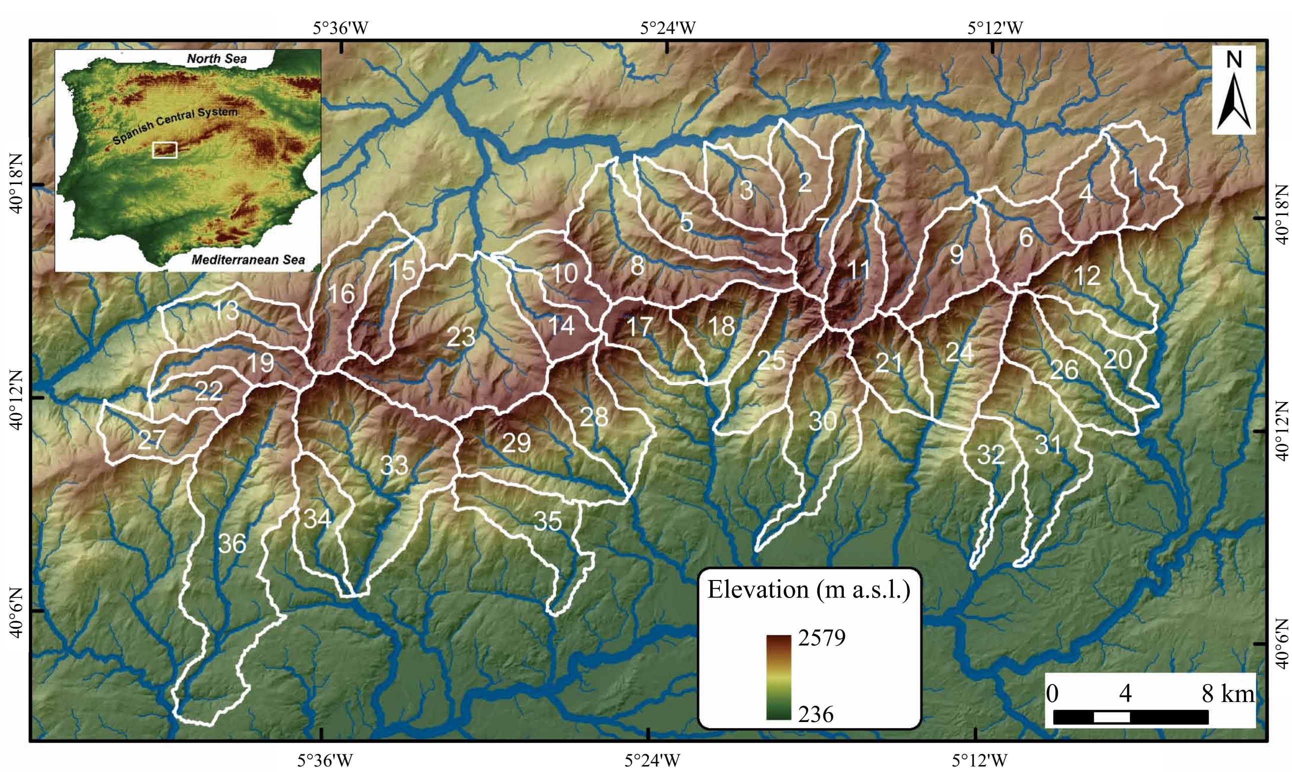

Figure 1. Location map of the study area. The inset map shows the location of Sierra de Gredos in the Spanish Central System. The numbers and white lines correspond to the study basins.

arrangement that started ~9 Ma (de Bruijne and Andriessen, 2002) and that still continues as the shallow seismicity records indicate (Cotilla *et al.*, 2007). The divide line of SG (Figure 1) corresponds to the lip of a thrust fault where the hanging wall faces northward (Babín and Gómez, 1997).

Glaciations in Sierra de Gredos

The Quaternary glacial advances and glacial landforms of SG and nearby ranges of the Spanish Central System were early recognized in the 19th century. Since then, several studies, mostly cartographic, have been published (Carrasco and Pedraza, 1995; Carrasco *et al.*, 2008). The timing and reconstruction of glacial advances for Sierra de Gredos and nearby ranges has not been completed yet since the chronology of glaciation was based on a relative chronology linked to the glaciation of the Alps (*cf.* Pedraza and Carrasco, 2006). Only recent studies carried out in the northern flank of SG (Palacios *et al.*, 2011, 2012) and in Sierra de Béjar (Carrasco *et al.*, 2012), a close range located northwest of SG, have provided absolute ages of the glacial advances during the LGM and their subsequent retreat, using cosmogenic dating techniques (Hughes and Woodward, 2008; García-Ruíz *et al.*, 2010; Palacios *et al.*, 2011, 2012; Carrasco *et al.*, 2012). The glaciation of SG correlates with the global LGM (Hughes and Woodward, 2008). The age of moraines found at the lowest elevation in Sierra de Béjar and SG has been dated between ~24 and ~27 ka (Palacios *et al.*, 2011, 2012; Carrasco *et al.*, 2012). There are neither geomorphic evidences nor ages of sediments that indicate the presence of older glacial advances. The LGM is believed to produce the most extensive glaciations in SG that erased any evidence of former glaciations (Palacios *et al.*, 2011, 2012).

Observations in SG and nearby ranges indicate that during the LGM, ice caps and ice fields formed on top of the sierras (Pedraza and Carrasco, 2006; Carrasco *et al.*, 2008). Glaciers flowing down the valleys where fed by ice caps (Carrasco *et al.*, 2008), that caused the formation of wide-open valleys, where the well-preserved moraines mark the maximum extent of the LGM (*e.g.*, Carrasco and Pedraza, 1995; Carrasco *et al.*, 2012; Palacios *et al.*, 2011; 2012). Parallel valleys of massive granites characterize the topography of SG (Figure 1). Glacial landforms such as moraines and cirques are well preserved on the northern flank of the sierra where valleys were fully glaciated and left the now well-preserved moraines. The glaciation of valleys in the southern flank was moderate resulting in the formation of cirques and moraines confined to the top of the ranges. The available cosmogenic ^{36}Cl ages (Palacios *et al.*, 2011, 2012) are from moraines in the Gredos and Pinar gorges (Basins 7 and 11 of Figure 1), both located in the northern flank. The age of the farthest moraine found in Gredos gorge is ~23 ka and ~17 ka in Pinar gorge; both ages are interpreted as the maximum glacial advance detected in SG (Palacios *et al.*, 2011, 2012). The ages obtained by Palacios *et al.*, (2011, 2012) approximate the maximum extent of glaciers estimated for Sierra de Béjar that occurred ~27 ka (Carrasco *et al.*, 2012). No other ages of moraines have been provided but their mean elevation at ~1700 m suggests that all are the same age. Reconstructions of the ice cap in Sierra de Béjar (Carrasco *et al.*, 2012), which was probably similar in SG, the exposure of polished bedrock and the mean elevation of moraines in SG, strongly indicate that the ELA during the LGM was ~1800 m (Pedraza and Carrasco, 2006; Palacios *et al.*, 2011, 2012). The position of the ELA during the LGM in SG falls in the range estimated for the ELA in the northwestern slopes of Sierra de Béjar (Carrasco *et al.*, 2012).

MATERIALS AND METHODS

Delineation and morphometry of the basins of Sierra de Gredos

The basins of SG were extracted from a flow accumulation map derived from a 25 m resolution digital elevation model (DEM), published by the Instituto Geográfico Nacional (IGN) and available in the IGN website (<http://www.ign.es>), using the hydrologic tools of the geographic information system (GIS) ArcGis 9.2 (ESRI). For the purpose of our analysis we selected those catchments with an area equal or greater than 10 km^2, that allowed us to include the fully glaciated and fluvial valleys. The glacial landforms of SG were identified using a 0.25 m resolution rectified, digital ortho-photos, available from the webpage of the Instituto Tecnológico Agrario de Castilla y León (<http://www.itacyl.es>), and consulting the satellite imagery of GoogleEarth. We supported our interpretation of glacial valleys with the existing geomorphologic maps (*e.g.*, Pedraza and Carrasco, 2006).

We set the limit of each basin at approximately the confluence of tributary rivers with the main trunk river. We avoided to include the joining of large valleys on each basin (Figure 1). We assessed the degree of glaciation on each basin using our interpretation of the glacial landforms. Our main criteria to identify marks of glaciations on each valley were: (1) the presence of lateral and frontal moraines, (2) the presence of wide-open valleys with flat bottoms, (3) the presence of cirques and (4) the exposure of large rounded bedrock surfaces that resemble the morphology of *roches moutonées*. The exposure of rounded bedrock surfaces is key in SG to identify signs of glacial erosion because granite does not crop out in non-glaciated areas and it is covered by a ~3 to 4 m-thick, red weathered mantle (Palacios *et al.*, 2011). We classified the basins of SG in three types, according to their degree of glaciation. Basins where glacial landforms cover ~75% were classified as fully glaciated basins. Glacial landforms exposed at high elevated areas that cover ~40% of the basin area were classified as

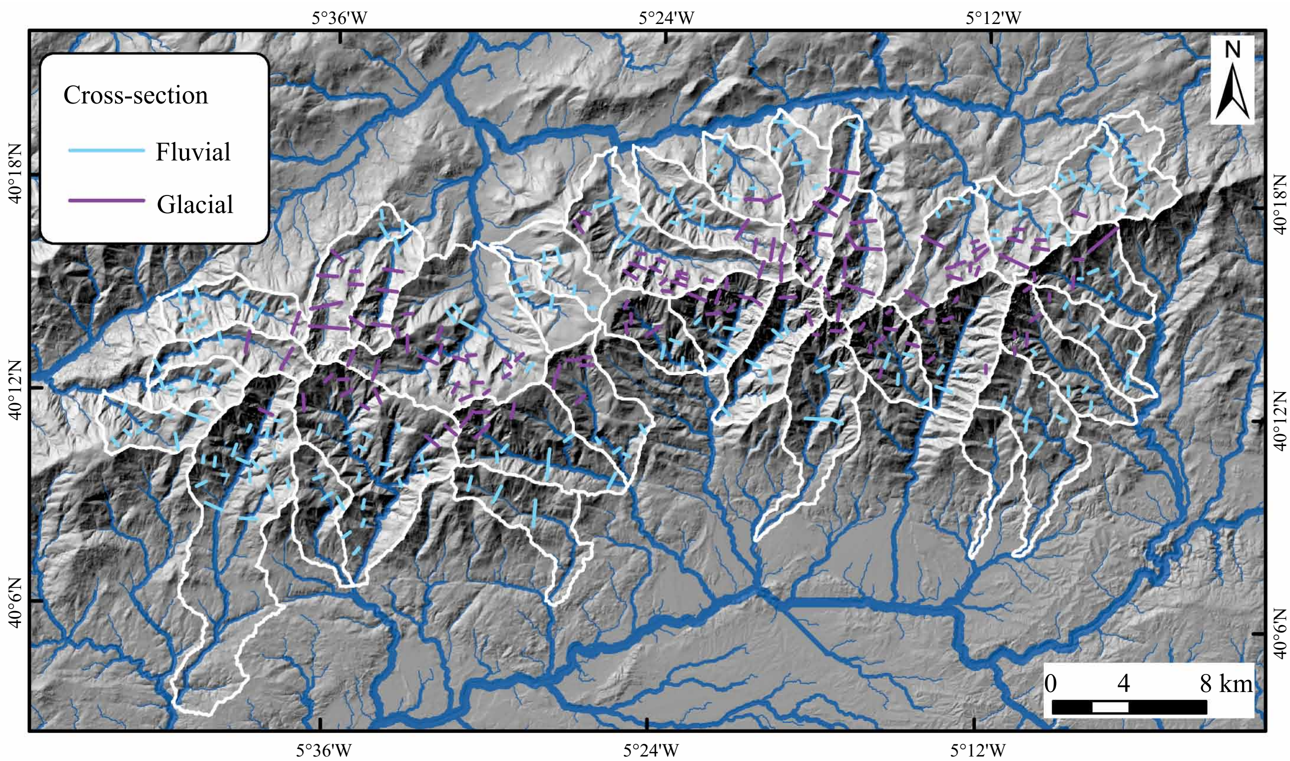

Figure 2. Map of the ridge-to-ridge cross-sections delineated for Sierra de Gredos.

moderate glaciated basins, and those basins which have not signs of glacial landforms or where glacial landforms are confined to the top of the range that do not exceed ~10% of the basin area, were classified as fluvial basins. We also separated the basins located on the northern and southern flanks of the range.

For each basin we determined means of elevation, local relief and channel k_{sn}. The mean basin elevation was estimated from the 25 m resolution DEM. The mean basin local relief, or what we termed here mean basins relief, was calculated following the approach of Montgomery and Brandon (2002) using grids of 1 km. The mean local relief was obtained only from those grids that were inside each basin. We also calculated the local relief above and below the LGM ELA (*i.e.*, 1800 m) for every 1-km-grid using as boundary all the basins delineated for SG.

To estimate the mean basin k_{sn} for each basin we used the stream profiler of the *geomorphtools* that are available at http://www.geomorphtools.org. We calculated the k_{sn} values (Wobus *et al.*, 2006) using a reference concavity (θ_{ref}) of 0.45 that allows comparisons with other mountainous settings (*e.g.*, Ouimet *et al.*, 2009; Cyr *et al.*, 2010). Because the k_{sn} is estimated from the slope-area regression of channels (Wobus *et al.*, 2006), this index also captures differences in climate, rock uplift, lithology and rock erodibility (Sklar and Dietrich, 1998; Whipple and Tucker, 1999). For the comparative analysis of the basins of SG we discard any effect of lithology and rock erodibility on the k_{sn} since the Hercynian (late Paleozoic) granite constitutes the whole lithology of the sierra. Thus, the k_{sn} allows us here to detect a forcing imposed by tectonics and/or climate.

We delineated a total of 316 ridge-to-ridge cross sections from which we obtained their width and relief. The relief was estimated using the highest flank of each valley. We distinguished between glacial cross-sections (Figure 2) using the same criteria as we did for the glacial basins. We also classified the cross-sections by their location on either the northern or southern flank. For the F_R we measured both the right and left flanks of valleys (n = 632) dividing the relief by two times the valley width. The F_R was used here to evaluate the deepening of valley or to detect whether the valleys of SG have reached the U-shaped morphology (Hirano and Aniya, 1988).

RESULTS

Relief production in the basins of Sierra de Gredos

The data compiled for each basin delineated in SG is presented in Table 1. In Figure 3a are shown the differences in elevation among fully glaciated, moderate glaciated and fluvial basins. The mean elevation of the fully glaciated basins is close to the LGM ELA (Figure 3a) and these are located only on the northern flank (Table 1, Figure 3b). The difference in the mean basin relief for each type of basins

Table 1. Location, classification and morphometry of the basins of Sierra de Gredos.

Basin ID	Latitude	Longitude	Area (km^2)	Mean elevation (m)	Mean k_{sn} value	Mean local relief (m)	Flank*	Type
1	-5.1072	40.3182	12.8	1723 ± 150	53 ± 28	181 ± 39	1	Fluvial
2	-5.3167	40.3148	11.7	1615 ± 199	82 ± 25	288 ± 28	1	Moderate glaciation
3	-5.3498	40.3072	14.1	1640 ± 254	95 ± 32	330 ± 77	1	Moderate glaciation
4	-5.1373	40.3089	13.7	1788 ± 182	63 ± 22	255 ± 74	1	Fluvial
5	-5.3758	40.2917	21.6	1681 ± 310	89 ± 41	375 ± 71	1	Moderate glaciation
6	-5.1782	40.2885	16.1	1816 ± 200	67 ± 24	287 ± 83	1	Moderate glaciation
7	-5.2991	40.2954	15.3	1845 ± 279	89 ± 46	431 ± 20	1	Fully glaciated
8	-5.4074	40.2766	35.7	1726 ± 306	98 ± 41	405 ± 80	1	Fully glaciated
9	-5.2229	40.2754	18.8	1845 ± 179	66 ± 23	272 ± 69	1	Moderate glaciation
10	-5.4615	40.2658	13.4	1783 ± 310	115 ± 67	371 ± 89	1	Fluvial
11	-5.2804	40.2711	16.6	2001 ± 228	87 ± 39	471 ± 31	1	Fully glaciated
12	-5.1325	40.2661	19.6	1400 ± 393	127 ± 41	400 ± 132	2	Moderate glaciation
13	-5.6610	40.2390	17.8	1450 ± 331	120 ± 35	446 ± 52	1	Fluvial
14	-5.4679	40.2457	11.3	1837 ± 330	94 ± 66	343 ± 158	1	Fluvial
15	-5.5681	40.2509	12.8	1755 ± 286	101 ± 45	434 ± 77	1	Fully glaciated
16	-5.5920	40.2535	18.7	1746 ± 294	88 ± 36	392 ± 90	1	Fully glaciated
17	-5.4034	40.2359	14.1	1627 ± 410	146 ± 67	528 ± 107	2	Moderate glaciation
18	-5.3596	40.2431	17.0	1551 ± 362	148 ± 42	545 ± 86	2	Moderate glaciation
19	-5.6581	40.2190	14.4	1755 ± 249	98 ± 47	329 ± 84	1	Moderate glaciation
20	-5.1300	40.2368	14.2	1059 ± 343	102 ± 56	295 ± 32	2	Fluvial
21	-5.2572	40.2273	15.3	1512 ± 394	151 ± 36	520 ± 58	2	Moderate glaciation
22	-5.6795	40.2037	10.3	1653 ± 230	109 ± 45	344 ± 21	1	Fluvial
23	-5.5233	40.2305	57.3	1678 ± 300	88 ± 44	349 ± 95	1	Fully glaciated
24	-5.2131	40.2339	25.8	1494 ± 358	146 ± 47	517 ± 86	2	Moderate glaciation
25	-5.3305	40.2271	20.7	1471 ± 466	161 ± 57	571 ± 97	2	Moderate glaciation
26	-5.1522	40.2267	20.6	1186 ± 434	116 ± 35	477 ± 118	2	Moderate glaciation
27	-5.7066	40.1845	13.3	1486 ± 227	117 ± 74	379 ± 91	1	Fluvial
28	-5.4354	40.1995	20.2	1408 ± 421	134 ± 63	438 ± 62	2	Moderate glaciation
29	-5.4744	40.1812	30.9	1365 ± 449	151 ± 63	469 ± 104	2	Moderate glaciation
30	-5.2996	40.1998	28.6	1161 ± 497	123 ± 51	463 ± 117	2	Moderate glaciation
31	-5.1659	40.1912	26.1	937 ± 386	85 ± 48	299 ± 73	2	Fluvial
32	-5.1938	40.1807	10.6	861 ± 309	75 ± 30	429 ± 104	2	Fluvial
33	-5.5721	40.1731	53.6	1323 ± 454	134 ± 54	455 ± 78	2	Moderate glaciation
34	-5.6041	40.1464	14.7	1035 ± 360	112 ± 51	404 ± 103	2	Fluvial
35	-5.4744	40.1463	21.0	886 ± 362	85 ± 47	341 ± 107	2	Fluvial
36	-5.6553	40.1344	68.1	924 ± 488	85 ± 57	307 ± 193	2	Moderate glaciation

* 1 and 2 correspond to the north and south flank of Sierra de Gredos, respectively. k_{sn}: normalized steepness index.

is presented in Figure 3c. Those basins that had a moderate glaciation have higher relief than the fully glaciated and fluvial basins (Figure 3c). Even though the fully glaciated basins are located on the northern flank, their relief is modest when these are compared to the relief of the southern flank, where moderate and fluvial basins have the greatest relief (Figure 3d).

We detect a good correlation ($r^2 = 0.70$, $p < 0.001$) between the mean basin k_{sn} and mean basin relief (Figure 4). This trend is consistent with other settings where the river erosion rates are related to k_{sn} values (*e.g.*, Ouimet *et al.*, 2009; DiBiase *et al.*, 2010). Calculating the regression of the mean basin relief and the mean k_{sn} for the fully glaciated basins, moderated glaciated basins and fluvial basins, reveals that the correlation is valid for the last two (Figure 4). The mean basin elevation also shows a tight correlation with the mean basin k_{sn} on those basin located on the southern flank but it is not valid for the basins of the northern flank (Figure 5a). The basin relief of the glacial basins is linearly correlated to changes in elevation (Figure 5b). Our analysis of the local relief of the surface lying above and below the LGM ELA indicates that relief is significantly high (t test: $p < 0.01$) for the landscape lying below the LGM (Figure 6).

Relief and form of the valleys of Sierra de Gredos

Our analysis of ridge-to-ridge cross-sections reveals that the width of glacial valleys is significantly high (t test: $p < 0.01$) compared to glacial valleys on the southern flank and with fluvial valleys (Figure 7a). The relief of the glacial cross-sections is greater than those of the fluvial cross-sec-

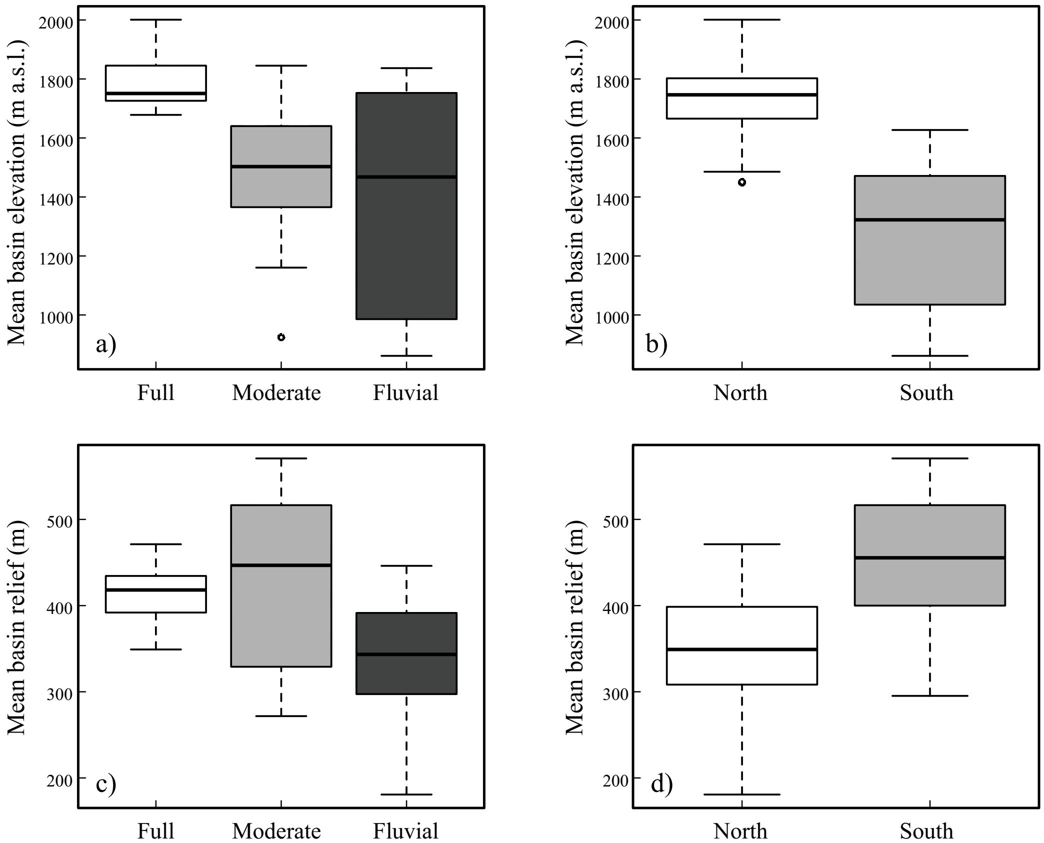

Figure 3. Box-and-whisker plots showing the difference in the mean elevation and mean relief according to the type and location of basins. The thick black line corresponds to the median and open circles to outliers. In a) the difference in elevation of fully glaciated basins is significant (t test: $p < 0.01$) compared to the moderate and fluvial basins. The box-and-whisker in b) reveals that the mean elevation of the basins located on the north flank is significantly high (t test: $p < 0.01$) of those located on the south flank. In c) is shown the mean relief for each type of basin. A significant low relief (t test: $p < 0.01$) characterizes fluvial basins compared to fully and moderate glaciated basins. The box-and-whisker plot in d) reveal a significant high relief (t test: $p < 0.01$) on the south flank of Sierra de Gredos.

tions (Figure 7b). There is not a significant difference (t test, $p > 0.05$) in the relief of the glacial cross-sections located in the northern and southern flanks. Our results reveal that the F_R of both glacial and fluvial valleys is greater in the southern flank. The F_R on the northern flank is significantly high (t test, $p < 0.01$) for the glaciated valleys compared to fluvial valleys. The same applies on the southern flank where glacial valleys have significantly higher (t test, $p < 0.01$) F_R than fluvial valleys.

DISCUSSION

The results from our basin analysis of SG indicate that during the LGM, glaciers increased the local relief (Figure 3c). Nevertheless, contrary to our initial expectations of large erosion rates on fully glaciated basins (Hallet *et al.*, 1996) and consequently, an increase in the local relief (*e.g.*, Montgomery, 2002), the relief of fully glaciated basins in SG is less than the relief of basins subjected to a moderate glaciation (Figure 3d). Interestingly, the greatest local relief is concentrated in the southern flank of the sierra (Figure 8) where are also concentrated the highest k_{sn} values (Figure 9). The correlation between the mean basin k_{sn} and basin relief shown in Figure 4, which holds for fluvial and moderate glaciated basins, is consistent with settings where the rate of rock uplift controls is related with the rates of erosion by rivers (*e.g.*, Safran *et al.*, 2005; Ouimet *et al.*, 2009; DiBiase *et al.*, 2010), which may also increase the local relief. We interpret that the lack of correlation between relief and the mean basin k_{sn} values of the fully glaciated basins (Figure 4) results from the lowering of bedrock at the bottom of valleys by glaciers. The glacial erosion modified the pre-existing channel topography, leaving a less steep profile, compared to fluvial valleys, which is typical of glacial valleys (Whipple *et al.*, 1999). Thus, the mean basin k_{sn} values of the fully glaciated basins are not capturing the rock uplift operating in SG, instead they represent the modifications made by glaciers on the bottom of glacial valleys. Such condition makes it difficult to unravel the control exerted by the rock uplift in erosion caused by glaciers.

Elevation also seems to be an important factor related to the relief production in SG. The correlation between the mean basin elevation and the mean basin k_{sn} values observed

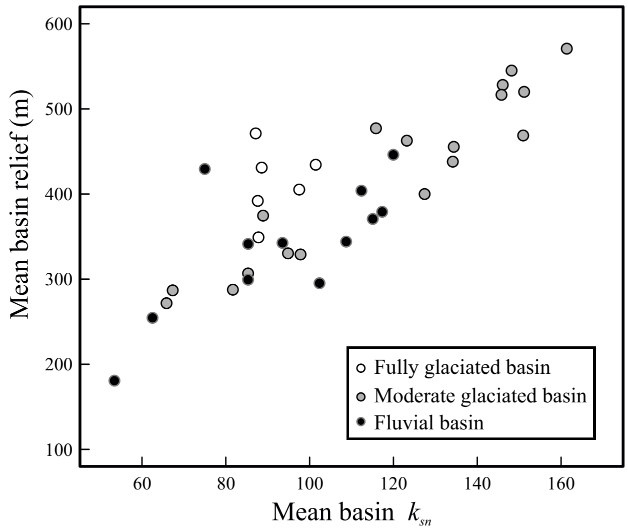

Figure 4. Correlation between the basin relief and mean basin normalized steepness index (k_{sn}) in Sierra de Gredos. The best correlation for all basins is by fitting a power law function. The regression for each type of basin reveals no correlation for the fully glaciated basins, a strong correlation for moderated glaciated basins ($r^2 = 90$, $p < 0.01$) and a fair to good correlation for fluvial basins ($r^2 = 0.59$, $p < 0.01$).

in the southern flank (Figure 5a) suggests that the rates of rock uplift increase linearly with altitude, and because of the existing correlation of Figure 4, the relief production is also likely to increase with elevation. Such model seems to be consistent with the tectonic setting of SG because the southern flank corresponds to the footwall of a thrust fault. Thus, high uplift rates are expected to increase with elevation because the fault scarp is being pushed upwards. For the case of the fully glaciated basins, the increase in relief with elevation is somewhat expected since the ice thickness of the ELA, which varies with altitude, is related with the basin relief (*e.g.*, Brocklehurst *et al.*, 2008). But the still unanswered question is why does the relief in the southern flank exceeds the relief observed in the fully glaciated basins of the northern flank?. We suspect that the ongoing rock uplift and bedrock fluvial incision are responsible for the relief production on the southern flank of SG. The less extensive glaciation on the southern flank lowered the summits, formed small cirques and ice accumulated at the bottom of cirques but it was not as intense as in the northern flank. The storage of glacial ice was of particular importance because it may have provided large meltwater discharges that increased the bedrock incision during summer season or at deglaciation. Recent observations in the Swiss Alps indicate that the relief production by rivers can be high after the onset of glaciations (Haeuselmann *et al.*, 2007; Valla *et al.*, 2011). Recent numerical models also indicate that the subglacial hydrology may also contribute to the deepening of valleys below the ELA (Herman *et al.*, 2011). The difference between the bottom valley profiles in the northern flank with the moderated glaciated valleys on the southern flank suggests that the glacial erosion in the later, was not able to dramatically modify the channel topography (Figure 10). It is highly possible that the glaciers in the southern flank served as water storages rather than being effective agents of erosion capable of increasing the local relief. This seems to be confirmed by the concave profiles, typical of rivers profiles (*e.g.*, Sklar and Dietrich, 1998; Whipple and Tucker, 1999) observed at the bottom of valleys of the

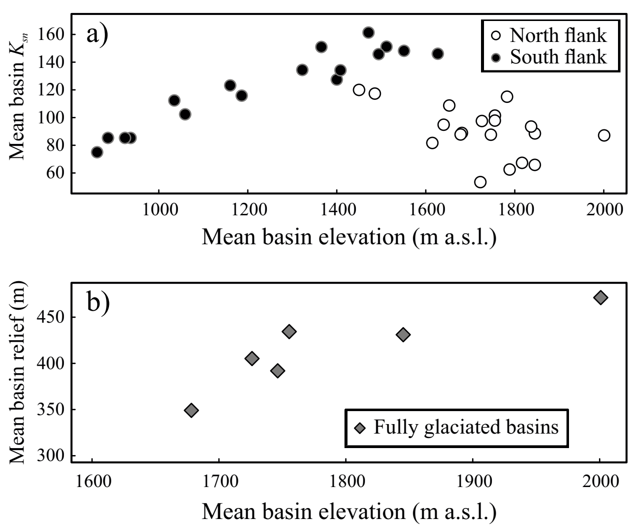

Figure 5. Controls on relief production on basins according to its type and location. In a) is shown the relationship between the basin normalized steepness index (k_{sn}) and elevation. For the south flank the tight correlation ($r^2 = 0.92$, $p< 0.01$) strongly suggest that the relief production increases with elevation. No correlation exists between basin k_{sn} and elevation for the north flank. b) shows a good correlation ($r^2 = 0.73$, $p< 0.05$) between basin relief and mean elevation, however, the basin k_{sn} is uncorrelated with the relief production (see Figure 5a).

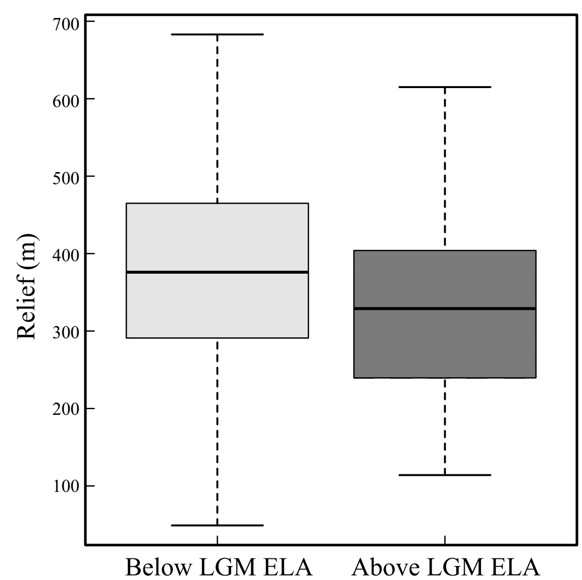

Figure 6. Whisker-and-box plot of the local relief above and below the Last Glacial Maximum equilibrium line of altitude (LGM ELA). The difference in local relief of the landscape below and above the ELA is significantly high (t test: $p < 0.01$) for the first.

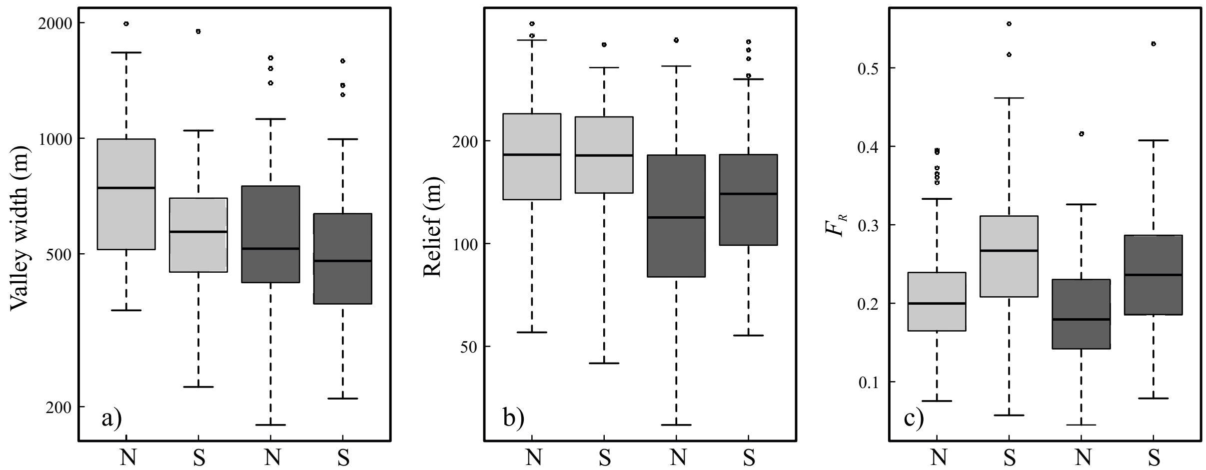

Figure 7. Whisker-and-box plots of (a) width, (b) relief, and (c) form ratio (F_R) of the cross-sections delineated for Sierra de Gredos. The light gray boxes correspond to cross-sections in glacial valleys and the dark gray boxes to fluvial valleys. The capital letters N and S correspond to the north and south flanks respectively. Note in a) the width of the glacial valleys located in the north flank. In b) it can be observed the greater relief of glacial valleys. In c) the highest F_R values correspond the valleys located on the south flank.

southern flank (Figure 10c and 10d).

The orientation of slopes has been invoked as an important control on the development of glacial landforms in the mountains of the Spanish Central System (*e.g.*, Muñoz *et al.*, 1995; Palacios *et al.*, 2003; Pedraza and Carrasco, 2006). Observations in Peñalara Mountains (Spanish Central System), which are located east of Sierra de Gredos, indicate that hillslope orientation is a topographic control on the snow accumulation pattern where westerly-orientated slopes have a deficit of snow accumulation given by their windward position. Thus, snow that is accumulated leeward of winds resulting in the glaciation and subsequent glacial erosion is concentrated on the easterly-orientated slopes (Palacios *et al.*, 2003). Such pattern explains the extensive glaciation on the northern flank, which receives less radiation, and the moderate glaciations on the southern where hillslopes receive more solar radiation. The high local relief on the glaciated valleys of the northern flank (Figure 10a and 10b) is around the ELA as it has been observed in other settings where landscape erosion was controlled by

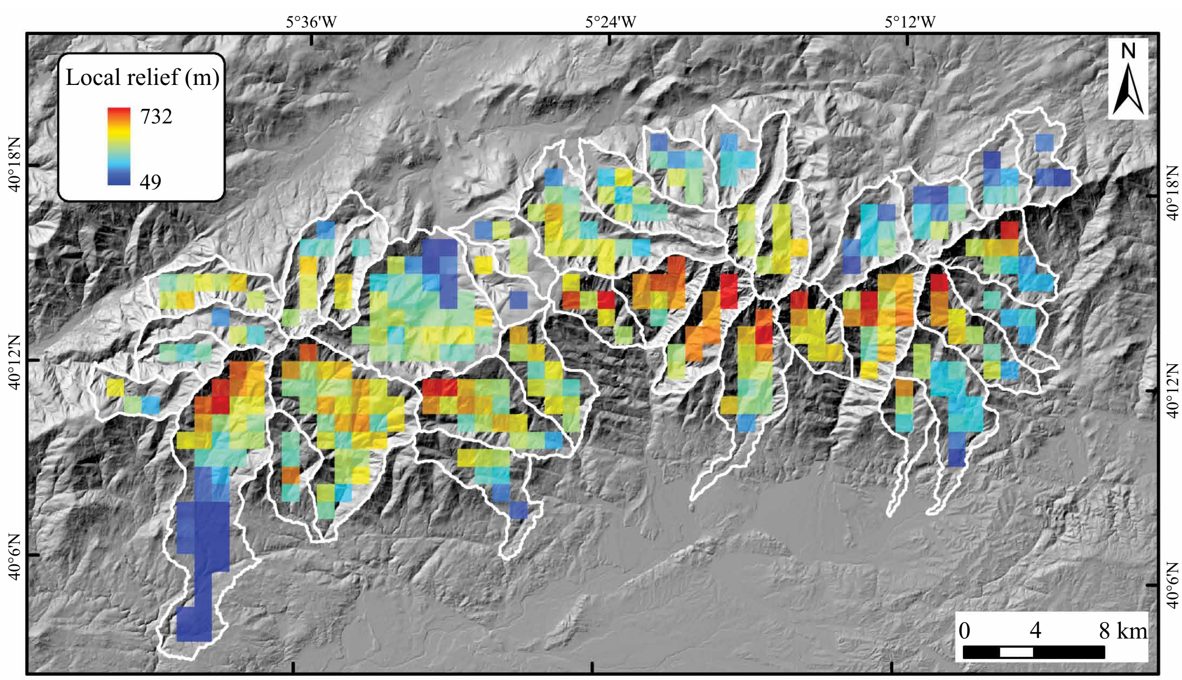

Figure 8. Map showing 1-km-grid local relief of Sierra de Gredos. The highest values of local relief are located on the high-elevated areas of the south flank.

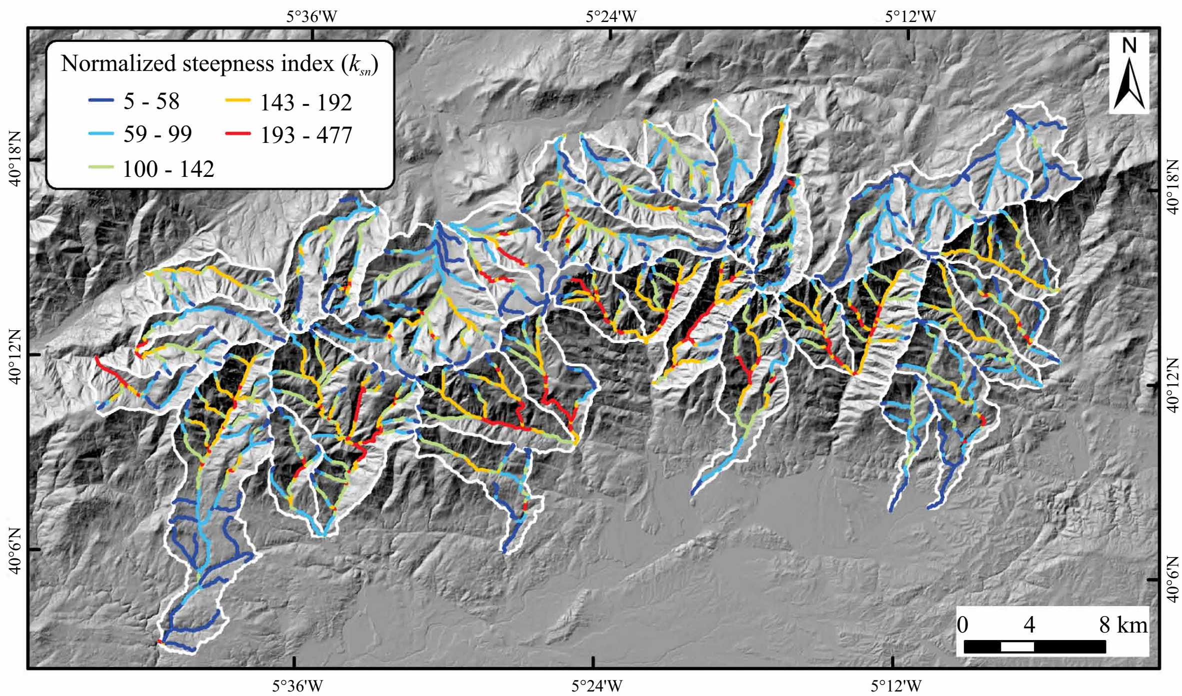

Figure 9. Map of normalized steepness index (k_{sn}) values of the streams of Sierra de Gredos. The highest k_{sn} values are concentrated on the south flank and keep a correlation with the local relief (Figure 8).

alpine-type glaciers (Brocklehurst and Whipple, 2002). The local relief on the moderated glaciated on the southern flank seems, however, independent of the ELA (Figure 10c and 10d). The lack of relationship between the local relief and the LGM ELA on the southern flank also supports our interpretation that high uplift rates and high rates of channel incision drive the relief production of the southern flank of SG. The lack of evidence of glaciations older than those of the LGM in SG, suggests that the LGM advances were intense enough to erase any former glacial advance, which probably occupied the same valleys as the glaciers of the LGM did. The LGM advances dramatically modified the topography of the northern flank of the sierra.

Our results of the glacial and non-glaciated cross-sections (Figure 2) also support our interpretations from our basins analysis. The width and great relief of the glacial cross-sections, particularly those located on the northern flank, indicate that glaciers modified the pre-existing topography by exhuming and polishing the granite bedrock and forming a knobby topography that is typical of the upper parts of glacial valleys (Anderson *et al.*, 2006a). The glaciers on the northern flank have lowered both the bottom of valleys and summits as do occur in other alpine type mountains (*e.g.*, Brockehurst and Whipple, 2002). Such erosion on top and bottom of valleys and hillslopes is consistent with the buzzsaw hypothesis where the local relief can be inhibited by an intense erosion of summits (*e.g.*, Brozovic *et al.*, 1997; Brocklehurst and Whipple, 2007; Egholm *et al.*, 2009). Our interpretation on the digital orthophotos and the low F_R values of the glacial valleys in the northern flank (Figure 7c) indicate that the overdeepening of valleys was not intense and prevailed the time enough to produce the full U-shaped morphology. It is interesting the fact though, that the F_R values of the southern flank valleys are high. The F_R values of the valleys located in the southern flank are likely to be highlighting the high relief production driven by the rock uplift as the concentration of high k_{sn} values suggest (Figure 9).

Finally, the significant difference found in the local relief between the areas lying above and below the LGM ELA (Figure 6), strongly suggests that the relief production on the fully glaciated areas and valleys (*i.e.*, glacial valleys on the north flank) was moderate because of the erosion of summits. The high relief observed below the LGM indicates that the relief production is controlled by high rates of uplift or high bedrock incision rates that were probably enhanced by meltwater discharge and/or the subglacial hydrology.

CONCLUSIONS

The glacial advances of the LGM in Sierra de Gredos, and particularly in the northern flank, dramatically modified the topography of the sierra by exhuming and polishing bedrock and forming extensive moraines. Even though the glaciers of the northern flank carved the bottom of valleys, the erosion of summits do also took place, resulting in a moderate relief production of ~70 m and ~45 m in basins and valleys respectively. The rates of rock uplift are high in the southern flank of SG, where the glaciation of valleys

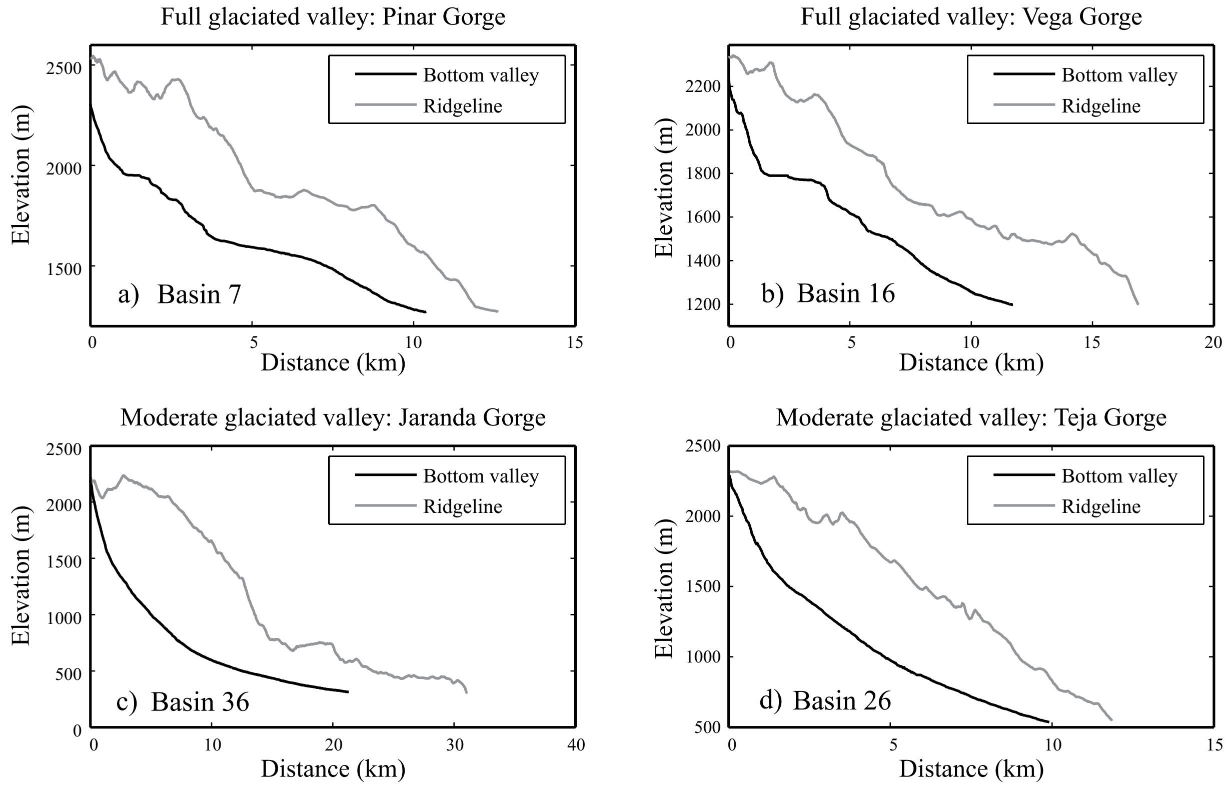

Figure 10. Bottom valley profiles of the north and south flank of Sierra de Gredos. In a) and b) are presented two bottom valley profiles of fully glaciated basins. In c) and d) are shown the profiles for moderate glaciated basins.

was moderate. Bedrock incision is likely to predominate in the southern flank which results in a local relief of ~87 m deeper than the relief observed in the northern flank where the extensive glaciations took place.

Our study of the basins and valleys of SG highlights two key points: (1) the control exerted by elevation and glacial erosion around the ELA where the relief production may be reduced by the lowering of summits as it is expected from the buzzsaw hypothesis, and (2) the high relief production caused by fluvial bedrock incision which responds to the rates of rock uplift and that are probably enhanced by the high discharge fed by the presence of glacial ice close to headwaters. Further research requires to unravel the response of glacial erosion to rock uplift in SG to answer if tectonics or the glaciation itself are responsible for the modest relief production of the sierra on its northern flank.

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