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Article

Are talus flatiron sequences in Spain climate-controlled landforms?

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with 4 figures and 2 tables

Summary. This study provides chronological evidence of the influence of climatic variability in the generation of late Quaternary talus flatiron sequences in Spain. The temporal clustering of the OSL and radiocarbon dates obtained from talus flatiron deposits indicates that warm/wet and cold/dry periods controlled the accumulation and incision processes in the slopes, respectively, that led to the development of talus flatirons. These results strongly suggest that talus flatiron sequences constitute valuable paleoclimatic records. Additional and more accurate geochronological data from Spain and other regions of the world would improve the potential of these poorly-known landforms in paleoenvironmental studies.

Key words: Please be so kind to insert 3–5 key words,

1 *Introduction*

The impact of past climate changes on geomorphic processes may be recorded by relict landforms and morpho-sedimentary sequences (e. g. moraines, fluvial terraces, speleothems, lacustrine terraces). Geomorphological analyses, especially when complemented with geochronological data, provide valuable information on past climatic variability and its influence on earth surface processes. Numerous studies have demonstrated the utility of some widely-known landforms for paleoclimatic reconstruction. However, it would be desirable to add new landforms to the suite of geomorphic features commonly targeted by geoscientists to infer paleoenvironmental information. The focus of this study is to analyze the chronological distribution of a considerable number of talus flatirons in Spain and to discuss the possible climatic implications of these landforms.

2 *Talus flatirons*

Talus flatirons, also termed triangular slope facets and tripartite slopes, are debris-covered relict slopes that were first described in the southwestern United States (Koons 1955). They are characteristic of semi-arid and arid environments (e.g. Northern Africa, the Middle East, the southwestern United States, Spain) and have also been documented in periglacial regions (Gutiérrez-Elorza 2005, Büdel 1970,

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Büdel 1982). These landforms typically develop at the foot of scarps in mesas, buttes and cuestas formed by erodible sediments overlain by a more resistant caprock. The initial slope profile consists of two segments; an upper caprock scarp and a lower debris-covered slope that may grade distally into a mantled pediment (Wood 1942, Schumm & Chorley 1966) or terrace (Sancho et al. 1988). Incision processes, accompanied by the retreat of the free face scarp, may result in the disconnection of the debris slope from the source area forming a talus flatiron (Fig. 1). Talus flatirons consist of erodible bedrock armoured by colluvial debris. Their shape is triangular or trapezoidal in plan view with the apex pointing toward the scarp. The gradient of these slopes with concave longitudinal profiles typically decreases from ca. 30° in the upper part to less than 5° in the distal part (Schmidt 1994, Gutiérrez Elorza et al. 1998a, Gutiérrez Elorza & Peña 1998). The caprock thickness constitutes a relevant conditioning factor for the development of talus flatirons, since it controls the scarp retreat rate and the colluvium thickness, which in turn influences dissection processes (Gutiérrez Elorza & Peña 1998, Gutiérrez Elorza et al. 1998b). Numerical dating of the colluvium covering these relict slopes allows for the estimation of scarp retreat rates by determining the position of the scarp when the debris slope was being formed by extrapolation. Scarp retreat rates of 0.9–1 mm/yr (Gutiérrez Elorza 2005, Gutiérrez Elorza & Sesé 2001) and 5–10.5 mm/yr (Gutiérrez Elorza et al. 2006) have been estimated using dated talus flatirons in two semiarid areas of Spain.

The generation of talus flatirons requires the alternation of accumulation and incision periods in the slopes. Successive cycles of accumulation and dissection produce sequences of talus flatirons (Sancho et al. 1988, Gutiérrez Elorza et al. 2006, Gutiérrez Elorza & Sesé 2001), whose relative chronology can be established according to their spatial distribution; the oldest flatirons are those located farthest away from the scarp (Fig. 1).

According to one of the genetic models, the generation of talus flatirons is controlled by local rock-fall accumulations that protect the underlying sediments favour-

Fig. 1. Talus flatiron sequence in the Ebro Tertiary Basin. The flatiron located furthest away from the scarp (S5) records the oldest preserved accumulation-incision cycle.

ing differential erosion (Koons 1955). Other authors propose that the formation of talus flatirons is governed by changes in climate that control the prevalence of erosion versus accumulation processes in the slopes (Sancho et al. 1988, Schmidt 1994, Gutiérrez Elorza & Sesé 2001, Gutiérrez Elorza et al. 2006, Arauzo et al. 1996). Some of these authors also indicate that, in recent times, human activities that result in a significant reduction in the vegetation cover (fire, overfarming/grazing) may have played a significant role in talus flatiron development (Everard 1963, Arauzo et al. 1996).

The working hypothesis is that the alternation of accumulation and incision processes that result in the generation of talus flatiron sequences in Spain are essentially controlled by climate variability. The geomorphic threshold that determines the balance between the prevalence of aggradation and gullying processes in the slopes is largely controlled by the vegetation cover, which in semiarid areas is highly sensitive to changes in climate (e. g. Morgan et al. 2008). Consequently, a decrease in precipitation or water availability may cause a reduction in the vegetation cover favouring the dissection of the slopes. Conversely, a rise in humidity may induce an increase in the vegetation cover favouring accumulation processes in the slopes.

3 *Geological setting and methodology*

A large number of talus flatirons have been identified and mapped in the three main Tertiary basins of Spain (Ebro, Tajo and Duero basins) (Fig. 2). These structural depressions, characterised by a semiarid climate, contain extensive mesas formed by erodible sediments capped by resistant Miocene limestones, which constitute a favourable geomorphic context for the development of talus flatiron sequences.

Detailed geomorphological maps have been constructed for each site in order to establish the relative chronology of the talus flatiron generations. Subsequently, a total of 31 absolute ages have been obtained from the talus flatiron deposits by optically stimulated luminescence (OSL) (21 samples) and radiocarbon (10 samples) dating; 14 from the Ebro Basin, 12 from the Tajo Basin and 5 from the Duero Basin. To our knowledge, these are the only available geochronological data of talus flatirons in the world (Tables 1 and 2). The OSL samples were collected by driving PVC tubes into the colluvial deposits. The values of environmental radiation were derived from available radiologic maps. The single-aliquot dates have been obtained by means of the additive doses method applied to fine particles (2–10 µm) in the Dating Laboratory of the Universidad Autónoma de Madrid. A previous anomalous decay test was performed based on the OSL response of the samples in a second measurement after storing them in the darkness during 240 hours. The anomalous decay phenomenon was considered negligible when the detected decay signal was lower than 3 %.

Pits were excavated using a pick and shovel to expose the colluvial deposits, typically consisting of massive gravels with fine-grained matrix less than 2 m thick (Fig. 3). Sandy facies and charcoal samples were preferably collected from the apical part of the flatirons and from the basal part of the colluvial sequence to avoid dating reworked (younger) deposits. In order to test the consistency between the two geochronological methods, samples for OSL and radiocarbon dating were collected from the same talus flatirons, although from a slightly different stratigraphic positions at two sites

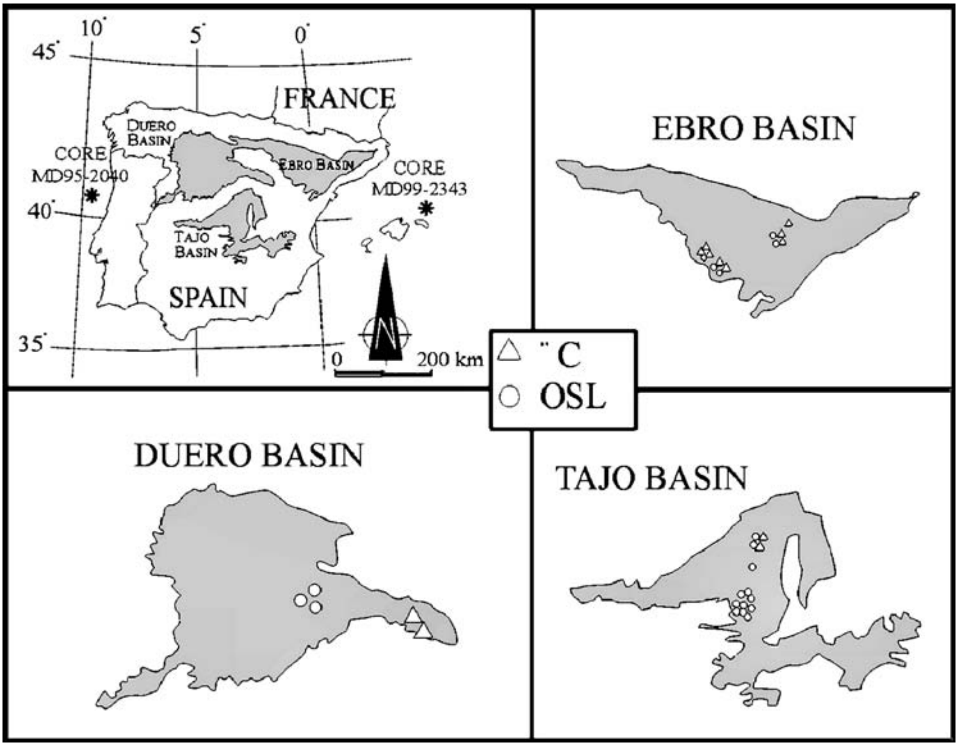

Fig. 2. Distribution of the dated talus flatirons in the main Spanish Tertiary Basins, and location of the marine cores used to analyse their climatic meaning.

showing a reasonable accordance. A relict slope in the Tajo Basin yielded radiocarbon and OSL ages of 29,690 ± 260 and 28,339 ± 1,782 yr BP, respectively (errors at 1σ). Radiocarbon and OSL ages of 41,450 ± 1,330 and 40,187 ± 3,275 yr BP (errors at 1σ) have been obtained from the same talus flatiron in the Ebro Basin.

4 *Results*

The geochronological data obtained for the talus flatiron deposits have significant limitations. On the one hand, the OSL dates have a very limited accuracy; the average and the standard deviation of the one-sigma age ranges of these dates are 5,349 and 1,512 years, respectively. On the other hand, the age of the talus flatiron accumulations is based on single dates due to the difficulty of obtaining datable material in the thin and coarse-grained slope deposits.

In spite of these drawbacks, the available dates show four temporal clusters that indicate a relationship during OIS 3 among warm/wet periods and the accumulation intervals in the slopes (Fig. 4). The chronological distribution of the obtained dates at one-sigma age range have been plotted alongside the Heinrich Events (HE) marked by the increase in the percentage of the cold foraminifer *Neogloboquadrina pachy-*

Table 1. Location and ages at the 1σ error margin of the OSL dated talus flatirons in the three main Tertiary basins of the Iberian Peninsula. The ages have been obtained in the Dating Laboratory of the Universidad Autónoma de Madrid (MAD).

Lab code	Tertiary basin	Site	Grid reference	Depth (cm)	Equivalent dose (Gy)	Annual dose (mGy/yr)	Th (ppm)	U (ppm)	K2O (%)	H_2O (%)	OSL age (yr.BP)
MAD-4,619	Duero	Cega	30TVL698867	80	109.59	3.57	4.06	1.26	1.20	14.56	30697 ± 2029
MAD-4,623	Duero	Peñafiel	30TVM087073	150	77.2	2.18	0.01	1.23	0.05	1.0	35412 ± 2,427
MAD-4,618	Duero	Cega	30TVL697865	50	95.84	2.46	1.48	0.69	0.85	20.20	38959 ± 2,543
MAD-4,798	Ebro	Candasnos	31TBG545040	40	129.00 ± 5.21	4.66	13.25	0.65	1.69	7.21	27682 ± 1,414
MAD-4,797	Ebro	Chalamera	31TBG625179	60	159.67 ± 8.3	5.05	6.35	2.91	1.55	3.86	31617 ± 1818
MAD-5,024	Ebro	Las Coronas	30TXL598868	110	88.25 ± 8.03	2.33	11.51	0.01	1.33	8.82	37875 ± 3,187
MAD-5,026	Ebro	Candasnos	31TBG533039	55	120.11 ± 9.83	3.05	6.95	0.91	2.27	6.03	39380 ± 2,971
MAD-5,023	Ebro	Candasnos	31TBG524042	70	96.45 ± 8.15	2.40	11.54	1.20	1.71	11.62	40187 ± 3,275
MAD-5,021R	Ebro	San Pablo	30TXL624819	45	140.11 ± 14.62	3.36	14.16	0.01	1.37	5.75	41699 ± 3,225
MAD-5,025	Ebro	Candasnos	31TBG531038	65	93.95 ± 5.33	1.80	7.30	0.42	1.05	10.55	52194 ± 3,170
MAD-5,022	Ebro	San Pablo	30TXL627817	130	157.80 ± 14.17	2.95	15.92	0.01	1.43	13.26	53491 ± 4,058
MAD-5,088	Tajo	Mesa de Ocaña	(4)541(44)084	60	45.06 ± 3.18	1.82	11.38	1.36	0.88	19.60	24758 ± 1,752
MAD-5,079	Tajo	Mesa de Ocaña	(4)549(44)084	125	45.85 ± 4.42	1.81	17.17	0.01	0.86	25	25331 ± 2,192
MAD-5,078	Tajo	Mesa de Ocaña	(4)547(44)085	60	32.45 ± 3.19	1.22	3.02	0.57	0.05	19.87	26598 ± 2,645
MAD-4,867	Tajo	Mesa de Ocaña	(4)524(44)094	50	61.15 ± 2.92	2.25	7.52	0.08	0.27	20.74	27177 ± 1,724
MAD-4,860	Tajo	Taracena	30TV906019	200	117.29 ± 6.26	4.13	22.04	0.01	1.09	5.43	28399 ± 1,782
MAD-4,859	Tajo	Taracena	30TV904010	55	108.31 ± 10.45	3.62	18.16	0.01	0.87	12.35	29919 ± 2,238
MAD-4,868	Tajo	Mesa de Ocaña	(4)523(44)094	105	72.40 ± 4.59	1.49	2.99	0.63	0.14	19.06	48590 ± 3,390
MAD-5,089	Tajo	Mesa de Ocaña	(4)537(44)250	300	111.59 ± 9.31	2.27	1.92	2.45	0.41	21.39	49158 ± 3,671
MAD-4,874	Tajo	Romanones	30TWK005920	90	133.4 ± 6.87	2.64	12.39	0.01	0.67	12.49	50530 ± 3,103
MAD-5,087R	Tajo	Mesa de Ocaña	(4)540(44)083	90	66.03 ± 3.02	1.25	1.19	1.41	0.01	25.40	52824 ± 3,555

Table 2. Location and ages at the 1σ error margin of the radiocarbon dated talus flatirons in the three main Tertiary basins of the Iberian Peninsula. The ages have been obtained in Beta Analytic Inc. (Beta) and in the Dating Service of the Universidad Autónoma de Barcelona (E).

Lab code	Tertiary Basin	Site	Grid reference	Material	Depth (cm)	δ13C(‰)	Conventional (yr. BP)	Radiocarbon age (BP) (1σ)
Beta-130256	Duero	Monteagudo	30TWL665754	Charcoal	15	−22.4	3590 ± 40	3855 ± 30 (AMS)
Beta-130254	Duero	Monteagudo	30TWL662761	Charcoal	300	−25.1	28550 ± 130	32963 ± 340 (AMS)
E-88	Ebro	Las Coronas	30TXL592872	Charcoal	100	−23.31 ± 0.15	25029 ± 52	2614 ± 100 (AMS)
Beta-85360	Ebro	Candasnos	31TBG537039	Charcoal	40	−25,0	2480 ± 80	2547,5 ± 187
Beta-80698	Ebro	San Pablo	30TXL627815	Charcoal	50	−25.0	2930 ± 60	3065 ± 100
E-89	Ebro	Las Coronas	30TXL593871	Ashes	40	−23.95 ± 0.15	27862 ± 444	32463 ± 429 (AMS)
Beta-80699	Ebro	San Pablo	30TXL623819	Charcoal	100	−24.1	35570 ± 490	40408 ± 948 (AMS)
Beta-216658	Ebro	Candasnos	31TBG524042	Charcoal	50	−23.2	41450 ± 1330	45041 ± 1349 (AMS)
Beta-179069	Tajo	Taracena	30TV906019	Charcoal	40	−24.9	25010 ± 180	29966 ± 284 (AMS)
Beta-225642	Tajo	Taracena	30TV906019	Charcoal	150	−23.8	29690 ± 260	33979 ± 306 (AMS)

derma (s.) analyzed in two marine cores that flank the study area, one from the Portuguese margin (De Abreu & Schackleton 2006) and the other from offshore Minorca island (Frigola et al. 2008).

The four temporal clusters, as defined by the time interval overlapped by the age range of three or two dates at the one-sigma error margin, are distributed as follows: Cluster 4 (55.2–47.4 cal kyr BP) occurs between HE6 and HE5, covering the long warm Dansgaard/Oeschger (D/O) interval numbered as 14 in the Greenland ice cores (Grootes & Stuiver 1997). Cluster 3 (42.2–36.4 cal kyr BP) covers from D/O interstadial 12 to the HE 4. Cluster 2 (33.2–23.8 cal kyr BP) is enclosed by HE 3 and HE2, thus overlapping D/O interstadials 3 and 2. Cluster 1 (2.6–2.4 cal. Kyr BP) occurs in the late Holocene after a long hiatus of around 20 kyr. This cluster overlaps with a phase of increased flood frequency between 2,880 and 2,430 cal yr BP inferred from slackwater flood deposits in Spain (Thorndycraft & Benito 2006)

In a previous work (Gutiérrez et al. 2006) based on a limited number of non-calibrated radiocarbon ages, a temporal relationship between slope agradation and Heinrich events has been suggested. However, the clusters defined by the larger number of ages presented in this work occur during warm/wet periods and disappear (Clusters 2 and 4) or decline (Cluster 3) during the cold HE. Furthermore, the gap of age dates between 24 and 4 ka coincides with the longest and coldest cold interval of the last 60 ka, covering the Last Glacial Maximum and the HE1, two periods characterized by very cold and dry conditions on the Iberian Peninsula (González Samperiz et al. 2006).

5 *Discussion and conclusions*

These chronological data strongly suggest that the alternation of accumulation and incision processes in the slopes that led to the development of talus flatiron sequences in Spain has been controlled by climate variability. For the youngest cluster aggrada-

Fig. 3. Pit excavated in the apex of a talus flatiron in Mesa de Ocaña, Tajo Basin. The deposits consist of an angular heterometric gravel with a fine-grained matrix.

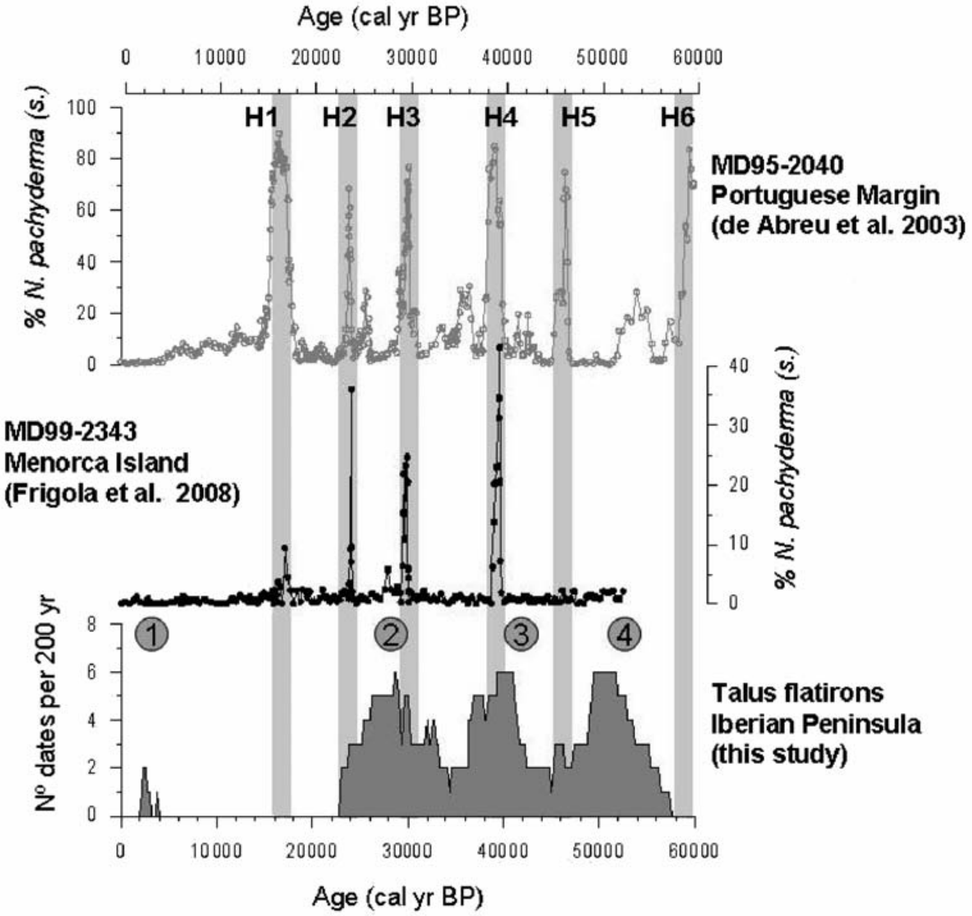

Fig. 4. The chronological distribution of the talus flatiron age ranges at one-sigma error margin plotted alongside the Heinrich Events (HE) marked by the increase in the percentage of the cold foraminifer *Neogloboquadrina pachyderma (s.)* in two marine cores situated to the east and west of the Iberian Peninsula.

tion in the slopes may have been also influenced by human activity. The correlation between the dating clusters and warm/wet periods indicates that the aggradation phases in the slopes occurred during time intervals in which higher water availability induced an increase in the vegetation cover, thus, inhibiting incision processes. Additionally, the coincidence of a long hiatus of time between 24 and 4 ka with a prolonged cold period in the late Pleistocene and early Holocene indicates that incision processes dominated in the slopes during cold periods with reduced precipitation and vegetation cover.

These results indicate that talus flatirons may constitute useful tools for paleoclimatic studies whose potential can be improved substantially. More precise ages should be established for the colluvial deposits of the talus flatiron sequences by obtaining multiple dates from each morpho-stratigraphic unit, using dating methods with uncertainties much lower than those yielded by the OSL technique (i. e. ^{14}C). This would allow the establishment of more refined correlations between the talus flatirons sequences and other paleoclimatic proxies and improving the potential of the talus flatiron sequences as paleoclimatic indicators. Additionally, it would be highly desirable to conduct similar investigations in other regions around the world in order to gain insight into the regional validity of our interpretations.

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