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Title: FIRE-RELATED DEBRIS FLOWS IN THE IBERIAN RANGE, SPAIN

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Abstract: Debris flows occurred three weeks following a wildfire in August 1986 in the Najerilla River valley in the Iberian Range, northern Spain. The flows were triggered by a brief, intense rainstorm (approximately 25 mm h-1 over 15 minutes) in a small area with steep slopes covered by a deep colluvium of quartzite clasts. This storm resulted in the development of several unconfined hillslope debris flows and the formation in the Pítare ravine of an alluvial fan, which partially blocked the Najerilla River. We analysed the conditions that led to the development of the debris flows, and estimated the rainfall threshold and the total volume of mobilised sediment. Four factors contributed to the debris flows: (i) the occurrence of a rainstorm three weeks following a wildfire, which had removed the plant cover from the soil; (ii) the steep slopes in the area were most affected by the debris flows (slopes > 30º); (iii) the presence of quartzite scarps on the hillslopes, which favoured the occurrence of a 'firehose effect' involving channelised surface runoff; and (iv) the low plasticity index values of the fine material of the colluvium (indices of 7 to 8), which enabled rapid liquefaction. Estimates of rainfall intensity from the peak flow in the Pítare ravine indicated that 81 mm of rainfall fell in 15 minutes, although this quantity was clearly overestimated given the high proportion of sediment carried out during the peak flow. Various equations applied to relatively similar conditions that occurred elsewhere indicated a rainfall-threshold of approximately 25 mm h-1 for a time of concentration of 15 minutes. The total sediment transported by the debris flows was 10,500 m3 (15,750 Mg, 6,800 Mg km-2), and the Pítare stream alone transported a minimum of 4,000 m3 (6,000 Mg, 2,500 Mg km-2). These results suggest that the rainfall threshold for initiating debris flows is decreased following a wildfire such that a typical rainstorm can trigger a severe erosion and sediment transport event. Given the absence of fresh landslide scars on the hillslopes, the origin of the fire-related debris flows in the Najerilla River valley appears to have been directly linked to increased rates of hillslope runoff, with overland having a greater effect than infiltration for triggered landslides.

COVER LETTER EXPLAINING THE CHANGES INTRODUCED IN THE PAPER "FIRE-RELATED DEBRIS FLOWS IN THE IBERIAN RANGE, SPAIN"

Authors: José M. García-Ruiz, José Arnáez, Amelia Gómez-Villar, Luis Ortigosa, Noemí Lana-Renault

We have corrected the paper carefully following the instructions and suggestions from the referees, to whom we acknowledge their detailed work, which helped us to significantly improve the content of the paper. For this reason we include a short reference to the referees in the "Aknowledgements" section.

These are the changes we have introduced:

Reviewer 1

-"The study is too descriptive". We have estimated both the intensity of precipitation and the volume mobilised by debris flows, and also we have applied some equations in order to compare our results with those from other authors. We have introduced some sentences explaining that the rainfall threshold for initiating debris flows was lower following the wildfire.

-"The open questions listed at the end of the Introduction are not answered". First of all, the order of the questions has been changed according to their relative importance. Secondly, all the questions have been answered in the Results and, mainly in the Discussion-Conclusions sections, by introducing some appropriate sentences.

-"The structure should be improved". Some changes have been introduced in the order of the sections (for instance, the study area has been placed before the methods), including the organisation of sub-sections in the Results section.

-"Figures should be strongly improved". Several changes have been introduced in the figures. Some of them have been eliminated, a new one has been incorporated and specific changes have been included in others. Nevertheless, some of the photos have been maintained, although they have not been considered necessary by reviewer 1, because they show some of the morphological characteristics of the debris flows and of the landscape (for instance, the presence of quartzite scarps upslope the initiation of debris flows).

-"English should be checked". Done. After the correction of the manuscript we sent the paper to the English correction service of Elsevier and accepted all the changes suggested.

-“Equations should be numbered”. Done.

-“Delete de word ‘consequences’ in the title”. Done.

-The concept of ‘liquefaction’ has been clarified in the Method section.

-“The samples were taken where and when?” The sampling points of clasts and fine material have been indicated in Figure 7.

-“Better explain the precipitation estimates”. The procedure for obtaining precipitation estimates was substantially changed, and includes more detailed explanations. Nevertheless, it is important to take into account that the result obtained is clearly an overestimate because it was derived from the peak flow, which in turn was also overestimated due to the importance of sediment transport.

-“Explain abbreviations” (e.g. “I10”). Done.

-Indicate all locations mentioned in the ms in a figure”. Done in Figure 1.

-“Lines 136-139: who did these calculations”. A reference has been added.

-“The area burnt by the fire should be indicated in a figure”. This was no possible because the area affected by the fire was much larger than that affected by debris flows.

-“In fig. 3, plant cover is the actual one, or the one previous to the fire?”. The plant cover shown in Fig. 3 is valid for both the pre-fire landscape and the actual landscape, due to a rapid re-colonisation with the same species.

-“Explain what could be the size of the storm”. In the text we note that the storm ought to be small, only affecting some square kilometres, because debris flows occurred in a small area.

-“Peak discharge estimates”: the discharge estimate has been explained in detail, indicating all the parameters used.

-“Clearly explain how you calculated the incredible rainfall intensity”. The procedure has been explained in the text, but the value obtained has not been considered to be valid; then, indirect values of precipitation have been obtained from other equations (Caine, 1980; Cannon et al., 2008) to have an order of magnitude of precipitation.

-The comparison of the triggering rainfall is not clear”. We have defined the minimum duration of the rainstorm according to the time of concentration, that is, 15 min.

-“Equations must be numbered”. Done. Besides, some corrections have been introduced.

-“Grain size. Indicate the maximum particle size observed”. Done. A short sentence has been added at the end of one of the paragraphs of the section 4.2.

-“Comment on liquefaction”. Done.

-“Scouring in m3/m”. Done.

-“Show characteristics described in point (iv) and (v)”. An extended explanation of the superficial grain size distribution has been added. Besides, Fig. 7 includes some histograms showing the different grain size distribution of the clast samples.

-The equations used to estimate the volume of the mobilised material were included in the Methods section.

-The Discussion and conclusions section has been considerably improved following the suggestions from the reviewers.

-Reviewer 1 doubts about the validity of the expression “so-called overland flow-caused debris flows”. It was taken from Wondzell and King (2003).

-“Did you observe this hydrophobic layer or it is speculation?” The original sentence has been deleted and a new sentence has been introduced in the last paragraph of the paper, indicating the possibility of the development of a hydrophobic layer on the soil surface, which is common during wildfires (Doerr et al., 2000), thereby contributing to a high level of runoff generation.

-“Table 1: add diameter of the different fractions”. Done.

“Table 2. Why the Pítare ravine is not included”. The reason is that no debris flows were observed in the Pítare basin.

Reviewer 2.

-“The Methods section does not include sufficient information about was done”. As explained above, important changes were introduced in the Methods section, with explanation of the equations and procedures.

-“Also in Methods, define and describe ‘scree’”. Done.

-“Figures need to include locations of all features referred to in the text”. Done.

-“The estimation of peak Q and the use of this value to estimate rainfall characteristics is not a solid result”. Many changes have been introduced for explaining the procedure used to obtain the peak flow and, indirectly, the rainfall intensity.

-“In Results, lines 237-239 indicate that clast size increased with distance”. New sentences and histograms in Fig. 7 add more information.

-The importance of the bedrock scarps has been underlined with some sentences in the Results and the Discussion sections. The absence of debris flow scars has also been highlighted in the Results section.

-The fact that the threshold conditions for generating debris flows from burned areas are lower than those under unburned conditions have been suggested in different parts of the text by: i) indicating that no debris flows have been triggered during the last 25 years in the same area, although intense rainstorms have been recorded in the area; and ii) estimating the rainfall necessary to trigger debris flows under unburned conditions (i.e., the equation from Ruiz-Villanueva et al., 2001).

-"Similarly, I did not see the data or analysis that indicates that debris flows mobilise more material than floods". This conclusion can be deduced by comparing the material mobilised by debris flows and by the flood occurred in the Pítare ravine.

- "Although steep slopes and the process of plant removal were indeed in existence, I didn't see data or analyses that would point to their importance in the generation of debris flows". We have not a clear response to this assertion. We deduce the importance of the steep slopes for the triggering of debris flows due to the occurrence of debris flows particularly in the steepest slopes. The same for plant removal: debris flows only occurred after the plant cover was burned.

-"The same holds true for the quartzite scarps, overland flow and clast removal". Debris flows initiate exactly at the foot of quartzite scarps, not upslope. Fig. 9 is a good example of this relation between scarps and debris flows.

Besides, the direct correction in the text made by Dr. Susan H. Cannon has also been accepted in most of cases. It was a tedious task for her that helped us very much to improve the text.

Highlights

Rainfall threshold for initiating debris flows (DF) is lower following a wildfire

DF mobilized much higher sediment yield than floods during the same rainfall event

Steep slopes and plant removal after wildfire are main factors triggering the DF

The presence of quartzite scarps on the slopes favoured channelized surface runoff

The studied DF were consequence of increasing rates of overland flow and clast removal

FIRE–RELATED DEBRIS FLOWS IN THE IBERIAN RANGE, SPAIN

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Abstract

Debris flows occurred three weeks following a wildfire in August 1986 in the Najerilla River valley in the Iberian Range, northern Spain. The flows were triggered by a brief, intense rainstorm (approximately 25 mm h^{-1} over 15 minutes) in a small area with steep slopes covered by a deep colluvium of quartzite clasts. This storm resulted in the development of several unconfined hillslope debris flows and the formation in the Pítare ravine of an alluvial fan, which partially blocked the Najerilla River. We analysed the conditions that led to the development of the debris flows, and estimated the rainfall threshold and the total volume of mobilised sediment. Four factors contributed to the debris flows: (i) the occurrence of a rainstorm three weeks following a wildfire, which had removed the plant cover from the soil; (ii) the steep slopes in the area were most affected by the debris flows (slopes > 30º); (iii) the presence of quartzite scarps on the hillslopes, which favoured the occurrence of a 'firehose effect' involving channelised surface runoff; and (iv) the low plasticity index values of the fine material of the colluvium (indices of 7 to 8), which enabled rapid liquefaction. Estimates of rainfall intensity from the peak flow in the Pítare ravine indicated that 81 mm of rainfall fell in 15 minutes, although this quantity was clearly overestimated given the high proportion of sediment carried out during the peak flow. Various equations applied to relatively similar conditions that occurred elsewhere indicated a rainfall-threshold of approximately 25 mm h^{-1} for a time of concentration of 15 minutes. The total sediment transported by the debris flows was 10,500 m^3 (15,750 Mg, 6,800 Mg km^{-2}), and the Pítare stream alone transported a minimum of 4,000 m^3 (6,000 Mg, 2,500 Mg km^{-2}). These results suggest that the rainfall threshold for initiating debris flows is decreased following a wildfire such that a typical rainstorm can trigger a severe erosion and sediment transport event. Given the absence of fresh landslide scars on the hillslopes, the origin of the fire-related debris flows in the Najerilla River valley appears to have been directly linked to increased rates of hillslope runoff, with overland having a greater effect than infiltration for triggered landslides.

Keywords: Debris flows, Sediment transport, Rainfall threshold, Wildfire, Iberian Range, Spain.

Introduction

Wildfires have been shown to be one of the most important factors controlling soil erosion and land degradation throughout the world (Cannon *et al.*, 2001a, 2001b; Moody and Martin, 2001; Wondzell and King, 2003; Shakesby and Doerr, 2006; Santi *et al.*, 2008). The absence of plant cover in the months following a wildfire, and associated changes in soil characteristics, can lead to the occurrence of very high erosion rates until the vegetation recovers 6-24 months later (Cerdà, 1998; Prosser and Williams, 1998), with sheet wash and rilling being the dominant erosion processes. The vulnerability of wildfire-affected steeplands to debris flows has frequently been cited in recent decades as the most important form of post-fire erosion, and such flows are capable of delivering tons of sediment in response to individual rainstorms (Swanson, 1981; Wells, 1987; Cannon *et al.*, 1997; Cannon and Reneau, 2000; Cannon *et al.*, 2001a, 2001b; Gabet, 2003; Beguería, 2006; Shakesby and Doerr, 2006; Gabet and Bookter, 2008; Gartner *et al.*, 2008; Santi *et al.*, 2008; Nyman *et al.*, 2011). Debris flows have commonly been related to shallow landslides triggered on sparsely vegetated hillslopes during intense rainstorms, which increase pore pressure and destabilise a portion of the slope (Blijenberg, 1998). Materials cleared by landslides become the main sediment source for debris flows (Johnson and Rodine, 1984; Blijenberg, 1998; Lorente *et al.*, 2002, 2003; Beguería, 2006; Bathurst *et al.*, 2007). However, recent reports have attributed the triggering of fire-related debris flows to increased rates of runoff eroding the uppermost areas of hillslopes (Cannon *et al.*, 2001a; Gabet and Bookter, 2008; Cannon *et al.*, 2011; Parise and Cannon, 2011). This fire-related erosion progressively increases the volume of sediment carried downslope, where concentration in zero- and first-order hollows leads to the evolution of debris flows. Nyman *et al.* (2011) noted that following a fire, most rills developed in previously unchannelised areas within the upper portion of the hillslope, thereby evolving as small and thin debris flows with levees prior to initiating channel scouring. In many cases, increased runoff has been related to the development of a hydrophobic layer (Cerdà, 1998; Prosser and Williams, 1998; Wondzell and King, 2003), consumption of the soil-mantle litter and duff (Moody and Martin, 2001), and limited rainfall interception by vegetation.

Fire-related debris flows are commonly reported in Spanish mountains, particularly the Pyrenees (Lorente *et al.*, 2002, 2003; Beguería 2006; García-Ruiz *et al.*, 2010) and the Iberian Range (García-Ruiz *et al.*, 1988). In most cases, the triggering of these debris flows has been attributed to periodical fires ignited by humans to convert shrublands to grasslands. For example, Lorente *et al.* (2002) reported that most debris flows in the mid-altitude belt of the Pyrenees occurred where fire frequently recurred, thereby resulting in degraded soils and open shrublands.

In the case of the Iberian Range, García-Ruiz *et al.* (1988) described a debris flow event during an intense rainstorm immediately following a wildfire in the Najerilla River valley. More than 20 years later, questions remain regarding the intense erosion caused by this single rainstorm: (i) what factors most strongly impact the generation of debris flows?; (ii) how much material was mobilised in the debris flows?; and (iii) what were the main characteristics of the rainfall event? This paper uses direct and indirect information to describe and explain the geomorphic consequences of the Najerilla River valley wildfire of 1986 and the subsequent rainstorm event.

2. Study area

The Najerilla River, which is a tributary of the Ebro River, runs from south to north through two of the main geostructural units in northern Spain: the Ebro Depression and the Iberian Range (Fig. 1). The area affected by the fire and debris flow event in 1986 was located in the upper part of the Sierra de la Demanda (Iberian Range). The Sierra de la Demanda is a Paleozoic massif raised by alpine tectonics (Lemartinel, 1985; Arnáez and García-Ruiz, 1990). Quartzite, shale, schist and sandstone with small limestone outcrops dominate the bedrock, which is intensely folded and faulted. The main drainage divide is approximately 1900-2100 m a.s.l., with secondary divides at lower altitudes. These drainage divides are considered to represent old erosion surfaces, as described by Arnáez and García-Ruiz (1990). The hillslopes are covered by a relatively deep mantle of scree (i.e. an accumulation of coarse, loose and angular clast-supported rock debris covers the hillslopes, with 20% fine material), which is partly active above 1800 m a.s.l. The hillslope gradients are very steep (> 20º; Fig. 2), and gradients > 40º are relatively common, particularly in the area most affected by debris flows. Scree is important in the hydromorphological behaviour of the massif because it is easily infiltrated by snowmelt and water from rainstorms, such that overland flow is rarely evident on the hillslopes (Arnáez, 1987). Erosion problems in the Sierra de la Demanda are primarily due to local deep-seated landslides, which are in turn associated with faults and the front of moraines, rills in the uppermost part of planar hillslopes, and a number of active headwaters of ravines.

The average annual precipitation is approximately 948 mm at the Valvanera weather station (4 km from the study area; 1020 m a.s.l.). Winter and spring are the wettest periods, whereas the summer is relatively dry (154.1 mm precipitation from July to September). Peak 10-intensities (I10) of 95 and 120 mm h^{-1} correspond to return periods of 10 and 25 years, respectively; for I30, intensities of 52.5 and 67 mm h^{-1} have been estimated for return periods of 10 and 25 years, respectively (De Salas-Regalado and Carrero-Díez, 2008).

Prior to the fire, the plant cover was dominated by common broom (*Cytisus scoparius)* and tree heather (*Erica arborea)*, with isolated stands of evergreen oaks (*Quercus rotundifolia),* thus forming a small forest in the southwestern part of the study area (Fig. 3). The recovery of the plant cover following the fire was rapid, and 25 years later most of the hillslopes have 100% vegetation cover, with a composition similar to that prior to the fire. In the area most affected by debris flows, the old cultivated, bench-terraced fields are scarcely visible, although their presence indicates that the farmers previously considered these slopes to be stable.

3. Methods

Altitude and gradient maps for the area affected by debris flows were obtained using the Digital Elevation Model (10 m^2) from the Regional Government of La Rioja. A vegetation map was also generated based on aerial photos and field studies.

The field studies at each individual debris flow involved three types of assessments: (i) The fine material was sampled at the source area to determine Atterberg limits and the plasticity index. These samples were collected 50 days following the rainstorm. (ii) Cross-sectional profiles were surveyed at various points along the debris flow pathway and runout area. The cross-profiles were performed using a theodolite with measuring points separated by 20 cm. (iii) The lengths of the longest axis of 100 clasts coinciding with the profiles were measured, using the Wolman's (1954) sampling procedure. Clast measurements were also performed in the source area talus scree.

Precipitation data for the storm were not available for the study area. Thus, the precipitation was indirectly estimated based on measurements of peak flow in the Pítare ravine, which was affected by a flash flood. The cross section, the height of the flood and the channel gradient were measured to estimate the peak flow using the Manning formula for open channels. The height of the water was deduced from the position of stems and branches deposited on both margins of the ravine. A Manning's roughness coefficient *(n)* of 0.1 was used, corresponding to natural channels with shrubs and trees, according to the table from Chow *et al*. (1988). After the maximum flow was calculated, the maximum rainfall intensity during the time of concentration of the Pítare ravine was estimated using the Rational formula; for this calculation it was necessary to estimate the runoff coefficient *C*. The time of concentration considered to be the minimum rainfall duration, which is based on the concept that the entire basin would contribute to the peak flow discharge. Values of *C* are generally high for small catchments with steep slopes (i.e. slopes with short times of concentration during high intensity rainfall). A *C* value of 80% was applied according to other studies in similar conditions (e.g., White *et al*., 1997). Equations from previous studies involving similar conditions were also applied, particularly those of Caine (1980) and Cannon *et al*. (2008), to provide comparable results in a broad context.

The total sediment volume mobilised by the debris flows was estimated based on the lengths and cross-sectional profiles of each debris flow. The sediment volume for each debris flow was estimated using two approaches (Fig. 4):

(i) For debris flows F-1 and F-4 the volume of accumulated sediment in the frontal lobe was estimated according to the following formula:

$$V = ((\pi \cdot R^2 \cdot \theta / 360) - (c \cdot h / 2)) \cdot L \qquad \text{(eq. 1)}$$

where V is the mobilised volume (m^3)

R is the radius of the frontal lobe (m)

θ is the central angle (degrees)

h is the height of the triangular portion (m)

L is the length of the accumulation sector

(ii) For debris flows F-2 and F-3 the volume of the incision was estimated by using the following formula:

$$V = (w \cdot d / 2) \cdot L \qquad \text{(eq. 2)}$$

where V is the mobilised volume (m^3)

w is the width of the debris flow incision (m)

d is the depth of the debris flow incision (m)

L is the length of the debris flow (m)

In the case of the Pítare ravine alluvial fan, the volume of sediment deposited during the rainstorm was estimated using five cross-sections of the accumulated sediment from the apex to the distal area of the fan. Then the area of each section was measured (m^2), as well as the distance between the sections (m).

The model of Gartner *et al.* (2008) was applied to estimate the volume of material mobilised from basins affected by fire-related debris flows.

4. Results

An intense, short-duration and spatially restricted precipitation event occurred in the Najerilla River valley on September 11, 1986, three weeks following a forest fire that occurred between 15 and 18 August, 1986 (García-Ruiz *et al.*, 1988). We deduced the short duration of the precipitation from the local population and newspapers (La Rioja, 12/09/1986). The spatially restricted character of the rainfall was deduced based on the area affected by debris flows, i.e., a small sector (approximately 5 km^2) located in the upper Najerilla River basin. Thus, the altitude of the burned area ranged from 765 to 1915 m a.s.l., occupying an area of approximately 1000 ha of shrubland and open forest, whereas the area most affected by debris flows occurred at approximately 800-1000 m a.s.l. Reliable rainfall records are not available for the study area, and therefore, only indirect estimates of precipitation are possible. At the Valvanera rain gauge, 4 km north of the burned area, 13 mm of precipitation were recorded. This is a relatively low level of accumulation, with a 50% probability of occurring in September. In the period following the 11 September rainstorm, many other similar or higher rainfall storms occurred in the area, which did not result in debris flows. It is noteworthy that although the fire affected greater than 1000 ha, the debris flows only occurred in a small area, thereby suggesting that the rainstorm effects may have been localised.

4.1. Rainfall analysis

An extreme flood occurred in the Pítare ravine and its effects enabled us to indirectly estimate the rainfall intensity that was involved. With an estimated velocity (V) of 3.65 m s^{-1} and a hydraulic radius of 1.63 m, a peak flow of 159 m^3 s^{-1} was estimated, the width, height and average gradient of the flooded channel were considered to be 23 m, 1.9 m, and 0.07 m m^{-1}, respectively, and Manning's *n* was established at 0.1. This peak flow was clearly overestimated (it would have represented an almost inconceivable specific discharge of 68 m^3 s^{-1} km^{-2}) due to three factors: (i) the large sediment load carried during the peak flow renders the method inappropriate; (ii) flow surges may have deposited stems and branches at somewhat higher elevations than would steady state flow; and (iii) erosional changes in the shape of the cross-sectional profile during the flood introduced large uncertainties in the method. As a result, the rainfall intensity estimated using the Rational formula will be too large for a runoff coefficient of 80%, i.e., 81 mm during the time of concentration (15 minutes, calculated for a basin with a length of 3150 m and a relief of 1060 m) with an intensity of 324 mm h-1. Clearly, such a value cannot be considered realistic because it would correspond to a return period greater than 500 years.

A comparison of our estimated storm rainfall with Caine's (1980) definition of the threshold rainfall conditions associated with failure of shallow landslides

$$I = 14.82D^{-0.39}, \qquad \text{(eq. 3)}$$

where I is the rainfall intensity (mm h^{-1}) and D is the duration of the rainfall (hours, 0.25 in the case of the rainstorm in the Najerilla River Valley), yielded an estimate of 25 mm hr^{-1} as the rainfall-intensity duration threshold necessary to trigger the debris flows that occurred. This level of intensity corresponds to a return period of four years. Cannon *et al*. (2008) developed empirical rainfall intensity-duration threshold equations for the occurrence of debris flows following wildfires in Colorado and southern California. Application of the first of these relationships ($I = 9.5D^{-07}$) (eq. 4) to the Najerilla valley fire yielded a rainfall threshold of 25.7 mm h^{-1} to produce the debris flows, whereas the application of the second equation ($I= 7.2D^{-04}$) (eq. 5) yielded a threshold of 12.5 mm h^{-1}. These threshold values are significantly less than the minimum rainfall estimated based on the peak flow in the Pítare ravine, thereby confirming that both results are overestimates or that the assumptions necessary to perform this estimate are not appropriate for the processes acting in the ravine.

Information based on the discharge in the Najerilla River at Anguiano was not a good indicator of the events that occurred. On the day prior to the rainstorm (10 September), the average discharge recorded at this site was 11 m^3 s^{-1}, and on the day of the storm, it was 11.5 m^3 s^{-1}; these data suggest that the rainstorm was highly localised, most likely affected an area < 10 km^2, or that discharges calculated as a daily average do not capture the response of the basin. Regardless, the locations of debris flows in a small sector of the Upper Najerilla River basin suggest that the storm had a highly localised characteristic, which is typical of many catastrophic Mediterranean rainstorms (White *et al*., 1997).

Ruiz-Villanueva *et al*. (2011) established a precipitation threshold equation ($I = 127.93D^{-0.71}$) (eq. 6) for the triggering of shallow landslides in an area of central Spain that was not previously affected by fire (Sierra de Gredos). When applied to the Najerilla case study, this formula yielded a rainfall intensity of 341.2 mm h^{-1} for 15 minutes. This estimate indicates that the occurrence of debris flows mobilised from shallow landslides would be nearly impossible in the Najerilla valley with presence of undisturbed vegetation.

4.2. Debris flows and the alluvial fan

Four debris flows and one alluvial fan developed during the rainstorm (Figs. 5-8). The debris flows had the following main geomorphic characteristics: (i) the debris flows had paths ranging between 240 and 896 m; (ii) scarcelly incised parallel rills were identified upslope of the quartzite scarps, thereby suggesting the occurrence of concentrated overland flow on the hillslope; (iii) in all cases, the debris flow deposits were located on very steep concave slopes dominated by quartzite scarps, and the primary sediment source for the debris flows was located at the foot of the quartzite scarps, where concentrated flow impacted the scree (Fig. 9); and (iv) no evidence of shallow landslide scars could be found in the area affected by debris flows.

Table 1 shows the particle size distribution in the sediment sources (i.e., the scree) where the debris flows developed. Debris flows F-2 and F-3 had a high proportion of sand (70-80%). Flows F-1 and F-4 had greater than 50% sand but were classified as loamy. A low clay content is typical of scree, because it is produced by physical weathering. The grain size distribution plays an important role in slope stability. For F-1 and F-3 the Atterberg limits and the plasticity index could not be determined because the samples liquefied immediately, reaching a zero effective stress in the soil mass (Iverson *et al.*, 1997). For F-2 and F-4, the plasticity indexes were relatively low (8 and 7, respectively), which indicates that once the plastic limit is reached, the deposit requires very little additional water to become liquefied.

Figures 5-8 show the shape and cross-sectional profiles along the paths of each debris flow, as well as the grain size distribution of the deposits. The cross-sections show five main similarities. (i) Scouring occurs between 3.7 and 8.3 m^3 m^{-1}. (ii) Sedimentation in the form of lateral levees is evident near the beginning of the incision (Fig. 10). (iii) A sedimentary lobe is evident towards the end of the incision, and, in specific cases, this is subdivided into several structures having convex cross-sectional profiles (Fig. 11). In the case of the F-1, F-2 and F-4 flows, the lobes contain most of the sediment eroded from the upslope region, as they do not connect with the fluvial network, although fine material was removed from the front of the lobes through small rills. In the case of F-3, the frontal lobe reached the channel of the Najerilla River, which was partially dammed by the debris flow for some days following the rainstorm. (iv) A progressive increase in the size of the clasts was detected in the levees and the frontal lobes. (v) The debris flow deposits show a larger clast size in the surface than the original talus scree, and the differences tend to increase towards the lower part of the slope, as shown in Fig. 7. This trend suggests that the mobilised deposit was affected by the sieve effect, such that the largest clasts were displaced to the surface. The maximum clast size observed was 570 mm, though the median size was around 185 mm on the surface of the mobilized deposits and 145 mm on the inner part of the scree.

An alluvial fan developed at the mouth of the Pítare ravine, thereby blocking the majoriry of the Najerilla River channel for several weeks. The presence of sediment on each margin of the channel suggests that the Pítare ravine behaved as a hyperconcentrated flow at some time during the event, although no evidence of debris flows was found in the hillslopes of its basin. The area of the fan was 0.3 ha; rapid scouring occurred following deposition, and plant colonisation ensued several years later (Gómez-Villar, 1996).

4.3. Volume analysis

We estimated the volume of sediment mobilised by the debris flows and in the Pítare ravine (equations 1 and 2) (Table 2). The total volume of sediment mobilised by the debris flows was approximately 10,500 m^3. Based on a bulk density of 1.5 t m^3, the debris flows transported approximately 15,750 Mg (6,800 Mg km^{-2}). The Pítare ravine transported at least 4,000 m^3 (6,000 Mg; 2,500 Mg km^{-2}). We compared these results with estimates obtained using the stepwise regression model of Gartner *et al.* (2008) for basins affected by fire-induced debris flows in the western USA. This model is defined as follows:

$$\ln V = 0.59 (\ln S) + 0.65 (B)^{1/2} + 0.18 R^{1/2} + 7.21 \qquad \text{(eq. 7)}$$

where V is the volume of a debris flow (m^3), S is the basin area with a gradient equal or greater than 30% (2.36 km^2), B is the total area of the burned basin (2.36 km^2), and R is the total rainfall during the rainstorm (25 mm).

Estimates obtained using this model for the four debris flows (15,000 m^3; i.e., 22,500 Mg) were greater than the total estimated based on the cross-sectional profiles in the study area. Nevertheless, these values are similar to within one order of magnitude, and thus, the differences are considered to be acceptable given the difficulties of calculating volumes mobilised by debris flows. In addition, it is important to note the uncertainty of the rainfall estimates.

5. Discussion and conclusions

An intense, short duration rainstorm several weeks following a wildfire in the Najerilla River valley triggered several debris flows and the formation of an alluvial fan. The Najerilla River was partially dammed by one of the flows and the alluvial fan. The total amount of sediment transported by the flows during the event was estimated to be 10,500 m^3 (15,750 Mg), thereby representing a one-time erosion rate of approximately 6,500 Mg km^2. The Pítare ravine transported at least 4,000 m^3 (6,000 Mg in total or 2,500 Mg km^2) of material, thus confirming that debris flows are capable of mobilising much higher sediment volumes than can floods during the same rainstorm event. This observation highlights the enormous potential of single events over extremely short time periods, and the resulting erosion can exceed soil erosion occurring over decades. For the Najerilla fire, estimates of the debris flow volume derived directly from the field were within the same order of magnitude as those obtained using the Gartner *et al*. (2008) model for basins affected by fire-related debris flows. It is important to note that the slopes affected by the debris flows were largely considered stable prior to the fire. This is typical of the hillslopes in the Sierra de la Demanda, even those having very steep gradients, due to the dense plant cover and the presence of a relatively deep colluvium, which favours infiltration and sub-superficial flow (Arnáez, 1987). The occurrence of several debris flows and the development of a new alluvial fan during an intense but not unusual rainstorm, and the lack of a comparable response in unburned setting, indicates that the wildfire caused accelerated erosion rates and lowered the erosion threshold. Moody and Martin (2001) reported a similar situation in Colorado (USA) where erosion after a wildfire in the Front Range resulted in an approximate 200-fold increase in erosion rates, thereby causing the frequent aggradation of alluvial fans (Mayer *et al*., 1992; Gómez-Villar *et al*., 2006). It is noteworthy that the triggering threshold of precipitation would be much higher in areas of undisturbed vegetation (Ruiz-Villanueva *et al*., 2011).

In general, debris flows are a relatively infrequent geomorphic phenomena in the Sierra de la Demanda (Arnáez and García-Ruiz, 1990). Since the September 1986 event, additional debris flows have not occurred in the fire-affected area, due to rapid plant colonisation, despite the occurrence of intense rainstorms. Unfortunately, the precipitation characteristics during the rainstorm can only be estimated indirectly, primarily based on the estimated discharge of the Pítare ravine. Because the discharge was clearly overestimated, the estimate of 81 mm rainfall in 15 min is also inaccurate, although extreme rainstorm events of 70 mm in 10 minutes or 69 mm in 8 minutes have since been recorded in the Central Pyrenees, near the study area (White *et al*., 1997; García-Ruiz *et al.,* 2002). If equations 3 and 4 are calculated for a time of concentration of 15 minutes, then the rainfall necessary to trigger debris flows in the Najerilla River Valley would be approximately 25 mm, that is, a frequent, high-intensity rainstorm (with a return period of four years). Similarly, debris flows generated during rainstorms with return periods of only two years (I30 = 31 mm h^{-1})

associated with a fire in Cerro Grande, New Mexico, USA (Cannon *et al*., 2001a), at Storm King Mountain, Colorado (Cannon *et al*., 1997), and in southeastern Australia (Nyman *et al*., 2011) have been described, thereby confirming that the initiation of fire-related debris flows do not require exceptional rainstorms. In addition, results obtained from a numerical model indicate that large rainstorms are not necessary to trigger thin debris flows on burnt slopes (Gabet, 2003; Lane *et al*., 2006). In a study of recently burnt areas in southwestern Colorado and southern California, Cannon *et al*. (2008) reported that storms triggering debris flows ranged in average intensity from 1.0 to 32 mm hr^{-1}, and had recurrence intervals of two years or less. These conditions can result in extremely dangerous fire-related debris flows because they can occur during relatively frequent rainstorms in areas where no debris flows have been previously observed (Cannon *et al*., 2008, 2011).

The Najerilla wildfire left the soil bare and affected the steepest slopes with gradients > 40º. Under these conditions, a relatively typical rainstorm event three weeks later was sufficient to cause a major erosion event. However, other factors could have contributed to generation of the debris flows. First, the low plasticity index of the fine material in the source area favoured liquefaction However, this factor alone is not sufficient to affect the generation of debris flows, due to the relatively low proportion of fine material in the deposits (20% of the total), and thus played a limited role in the stability of the original scree, which is likely stabilised by the repose angle of the clasts and their internal friction. A second factor is the presence of quartzite scarps on the slopes, which break the longitudinal profile and lead to a sudden increase in the energy of overland flow. Under such conditions the water flow, which concentrates in concavities, could impact the scree downslope of a cliff, thus mobilising large volumes of loose heterometric material in a process called the "firehose effect" (Johnson and Rodine,1984; Figs. 9 and 10). This effect is similar to the channel-bed failure studied by Gregoretti and Dalla Fontana (2007) in the debris flows of the Dolomites (northeastern Italian Alps) or by Calcaterra *et al.* (2007) in Campania, southern Italy. The "firehose effect" requires unique topographical and geomorphic conditions including steep slopes, concavities that concentrate overland flow, a scree deposit with loose material having a fine matrix that rapidly evolves into a liquid flow, and a scarp originating a small waterfall that strikes the scree and triggers the mass movement. These conditions were present at the origin of the F-2 and F-3 debris flows.

Scars typical of shallow land sliding were not found in the areas affected by the debris flows. This indicates that the fire-related debris flows studied were a consequence of increasing overland flow, which eroded the soil and the upper layers of the scree and progressively increased the volume of mobilised material downslope, as described by Wells (1987), Mayer and Wells (1997), Gabet and Bookter (2008) and Cannon *et al*. (2011). Ephemeral, parallel rills were observed in the upper part of the hillslopes, thereby suggesting the occurrence of high rates of runoff generation and erosion. Similar processes have been identified associated with other fire-related debris flows, including the Cerro Grande fire, New Mexico (Cannon *et al*., 2001 a), where sediment/runoff concentrations of 0.23-0.81 kg l^{-1} were measured in hillslope sediment traps. The formation of rills and gullies was also detected in the upper parts of debris flows at the Storm King Mountain, Colorado (Cannon *et al*., 1997, 2001b), in the Capulin Canyon fire, New Mexico (Cannon and Reneau, 2000) and in the Yellowstone National Park fire (Meyer and Wells, 1997). In a review of 46 debris flows in nine recently burnt areas in California, Utah and Colorado, Santi *et al*. (2008) concluded that channel erosion and scour were the dominant sediment sources for debris flows in the burned areas, whereas a study of the geomorphic consequences of wildfires in southeast Australia between 2003 and 2009 showed that sheet erosion and levee-lined rills on steep upper hillslopes were the most important sediment source for debris flows (Nyman *et al*., 2011).

Based on the absence of fresh scars on the hillslopes, the origins of the fire-related debris flows in the Najerilla River valley also appear to have been directly linked to increased rates of hillslope runoff, thus resulting in overland flow-caused debris flows (Wondzell and King, 2003) rather than infiltration-triggered soil slips. This type of flow initiation may be related to the development of a hydrophobic layer on the soil surface, which is common during wildfires (Doerr *et al*., 2000), thereby contributing to the high level of runoff generation (Gabet, 2003). Once concentrated, the runoff was able to entrain large quantities of sediment that scoured the concavities, which deepened into increasingly incised channels, and left levees on both margins of the debris flows. Finally, sedimentation in the form of lobate tongues directly occurred in the main river or in the lower part of the hillslopes, likely due to the loss of fine material and increasing roughness within the deposit. For two flows within the Najerilla River valley, this process was enhanced by the "firehose effect".

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FIGURE CAPTIONS

Figure 1. Map of the study area within the Sierra de la Demanda. The box indicates the area affected by debris flows.

Figure 2. Slope gradients in the study area. The locations of the debris flows and the Pítare ravine alluvial fan are shown.

Figure 3. Plant cover in the study area. The locations of the debris flows and the Pítare ravine alluvial fan are shown.

Figure 4. Parameters used for estimating the volume of sediment mobilised by debris flows F-1 and F-4 (left) and debris flows F-2 and F-3 (right). See the text for the explanation of the parameters.

Figure 5. Cross-section through debris flow deposit F-1. The legend also applies to Figs. 6-8.

Figure 6. Cross-section through debris flow deposit F-2.

Figure 7. Cross-section through debris flow deposit F-3. Histograms of clast size distribution in the debris flow levees and the original scree are also shown. Black dots indicate the sampling points for the clasts in the original scree; crosses indicate the sampling points for the fine material.

Figure 8. Cross-section through debris flow deposit F-4.

Figure 9. Debris flow F-3 incised into the scree at the foot of a quartzite cliff.

Figure 10. Debris flow F-1, with well-developed lateral levees.

Figure 11. Frontal sector of debris flow F-4, which is composed of a chaotic accumulation of blocks forming a convex lobe.

Table 1. Particle size distribution (%) of the fine material in the source areas

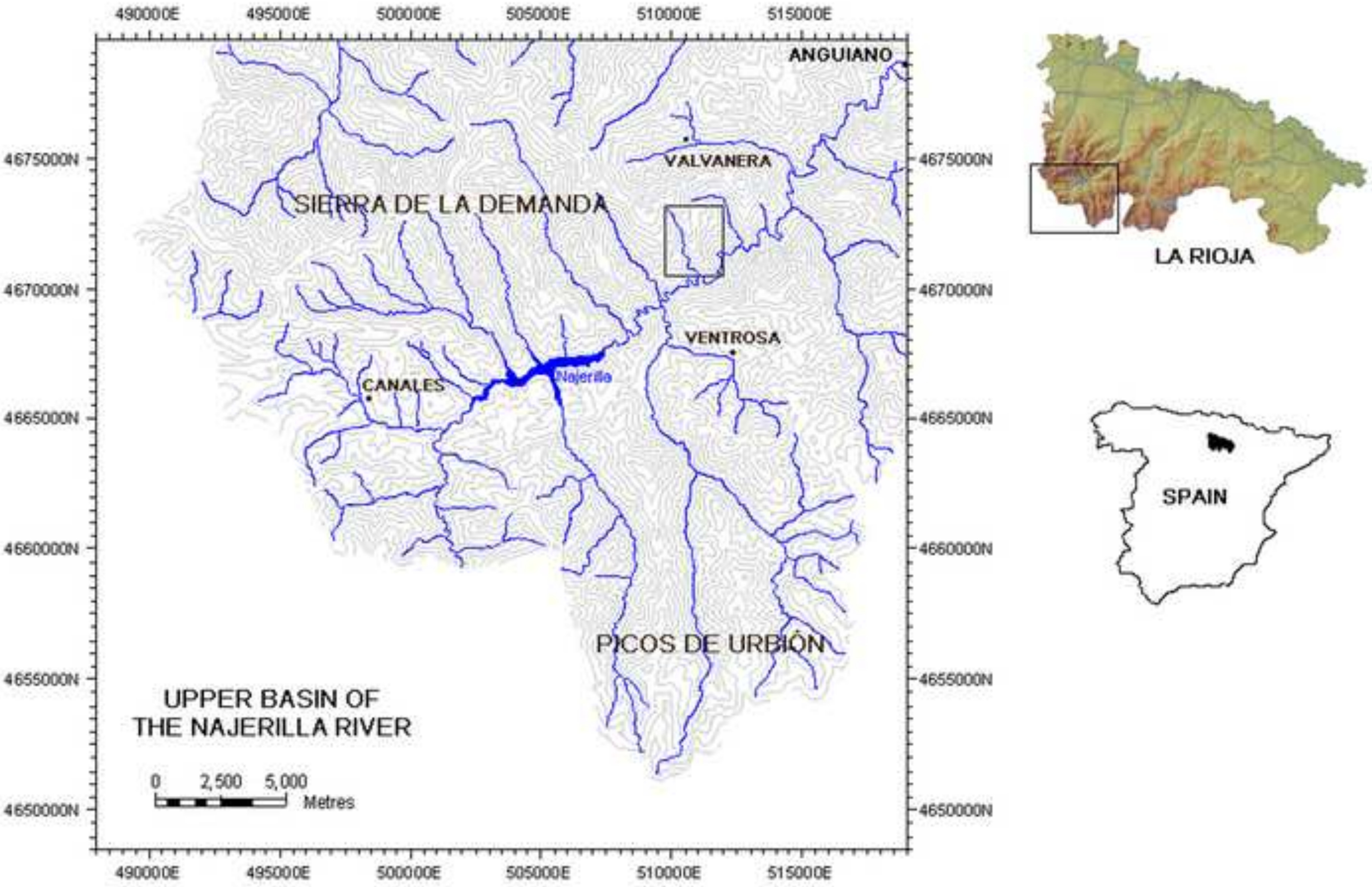
	F-1	F-2	F-3	F-4
Clay (<2 μm)	20.5	8.1	0.4	14.3
Fine silt (2-20 μm)	17.7	13.7	14.6	22.0
Coar. silt (20-50 μm)	7.2	8.1	7.7	11.9
Sand (>50 μm)	54.6	70.1	78.1	51.7
Classification	Sandy loam	Sandy loam	Loamy sand	Sandy loam

Table2

Table 2 Characteristics of the debris flows in the Najerilla Valley

	Maximum altitude (m)	Minimum altitude (m)	Average slope (º)	Total length (m)	Runout distance (m)	Estimated mobilised volume (m^3)	Volume mobil. by scouring ($m^3\ m^{-1}$)
Debris F1	1100	950	33.5	272	58	800	3.7
Debris F2	1220	850	33	685	172	2,900	5.6
Debris F3	1180	750	29	896	189	5,900	8.3
Debris F4	1100	970	33	240	58	900	4.9
TOTAL						10,500	

Figure1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ANGUIANO
VALVANERA
SIERRA DE LA DEMANDA
VENTROSA
CANALES
Najerilla
PICOS DE URBIÓN
UPPER BASIN OF
THE NAJERILLA RIVER
0
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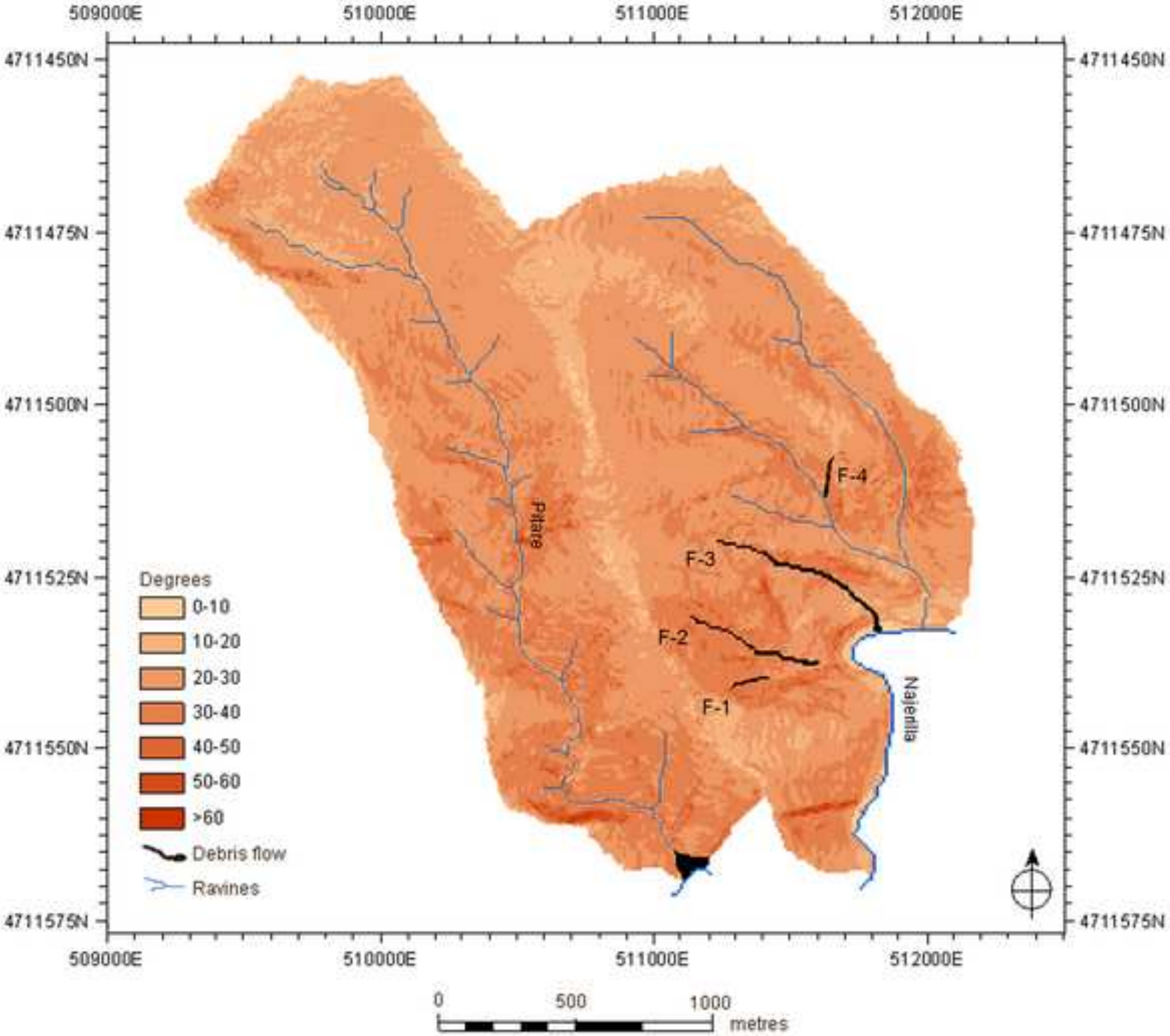
5,000
Metres
LA RIOJA
SPAIN

Figure2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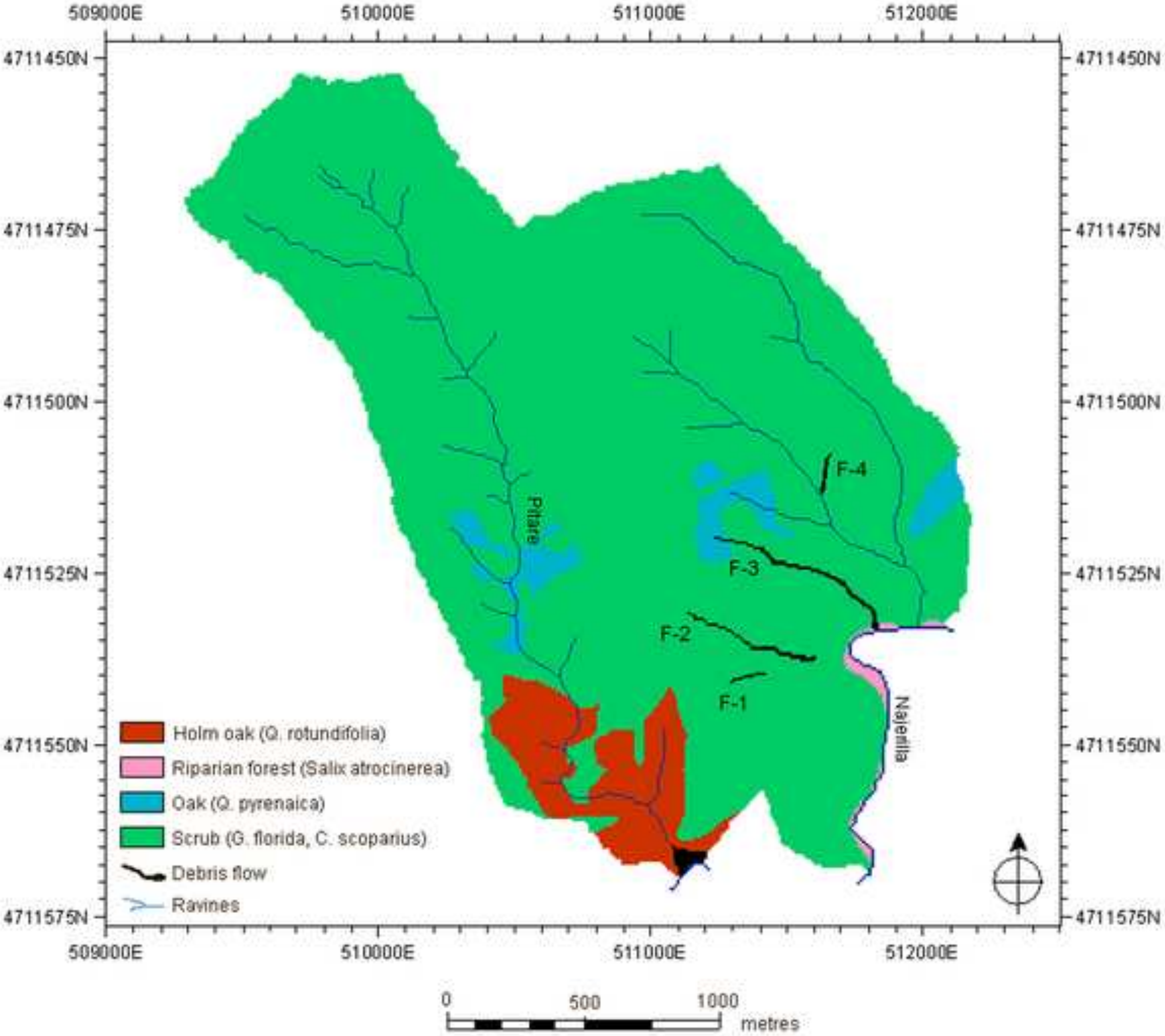
4711575N
Pitare
Najerilla
F-1
F-2
F-3
F-4
Degrees
0-10
10-20
20-30
30-40
40-50
50-60
>60
Debris flow
Ravines
0
500
1000
metres

Figure3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4711525N
4711550N
4711575N
Pitare
Najerilla
F-1
F-2
F-3
F-4
Holm oak (Q. rotundifolia)
Riparian forest (Salix atrocinerea)
Oak (Q. pyrenaica)
Scrub (G. florida, C. scoparius)
Debris flow
Ravines
0
500
1000
metres

Figure4

Figure5

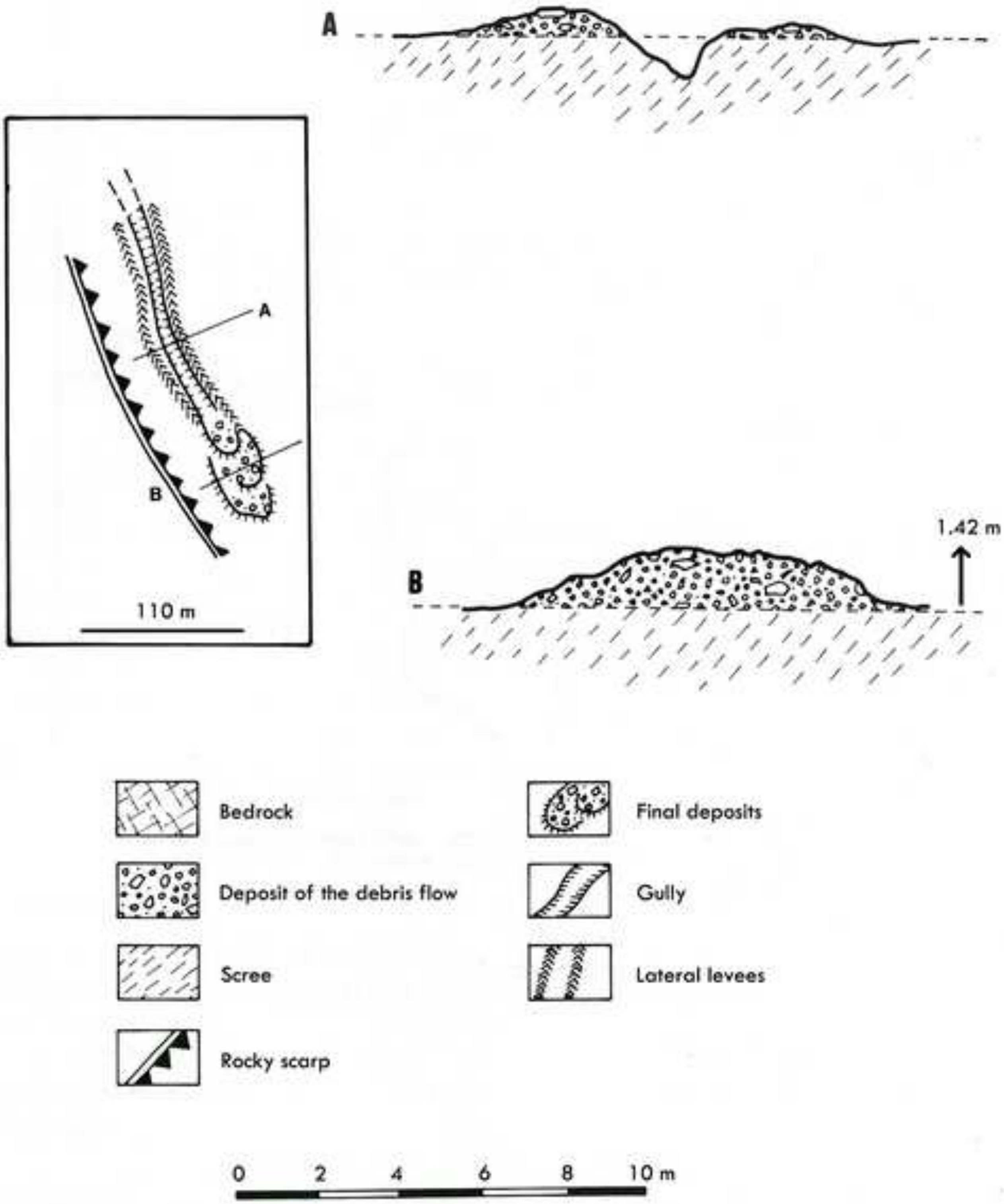

A
A
B
B
110 m
1.42 m
Bedrock
Deposit of the debris flow
Scree
Rocky scarp
Final deposits
Gully
Lateral levees
0
2
4
6
8
10 m

Figure6

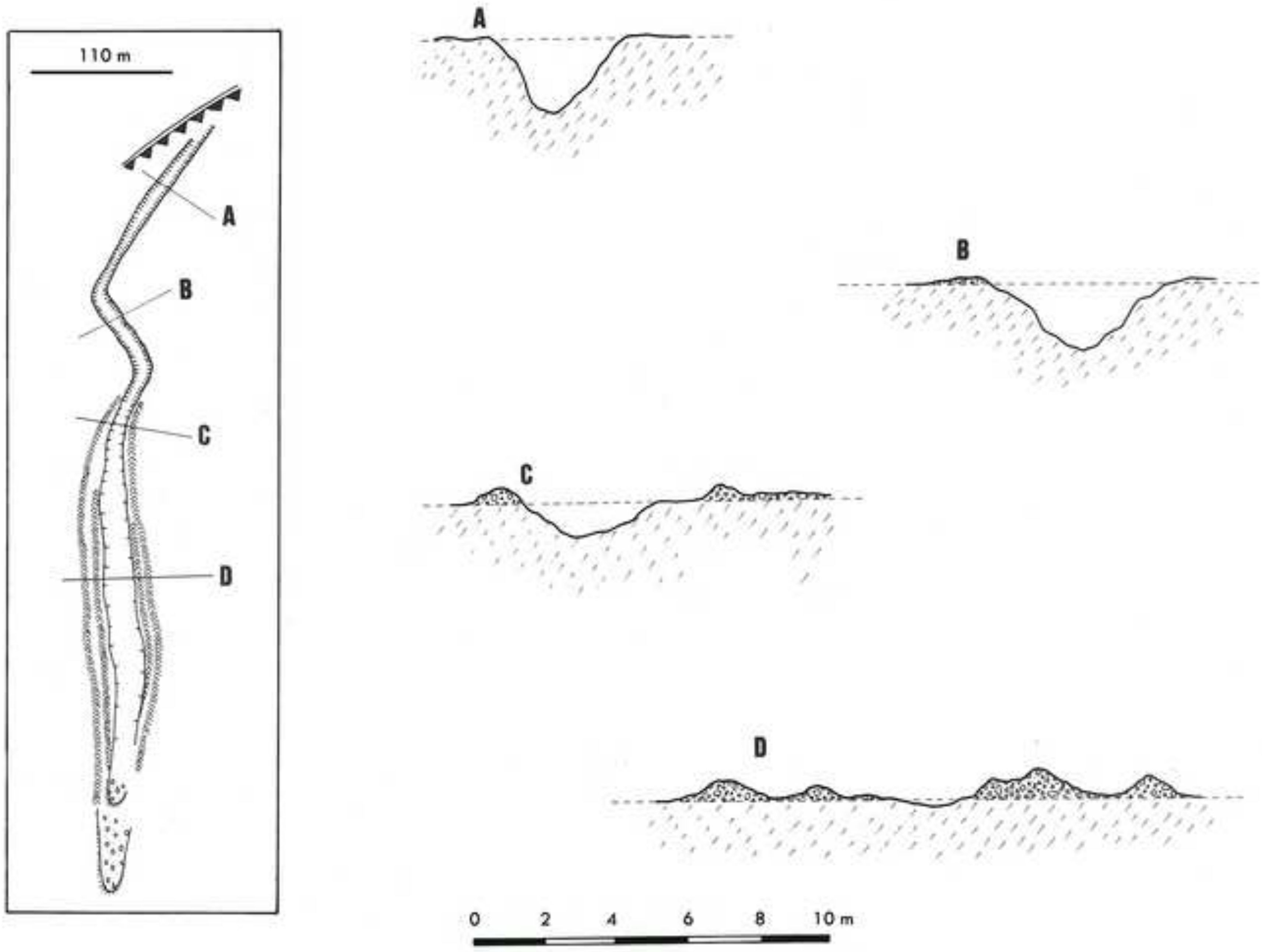
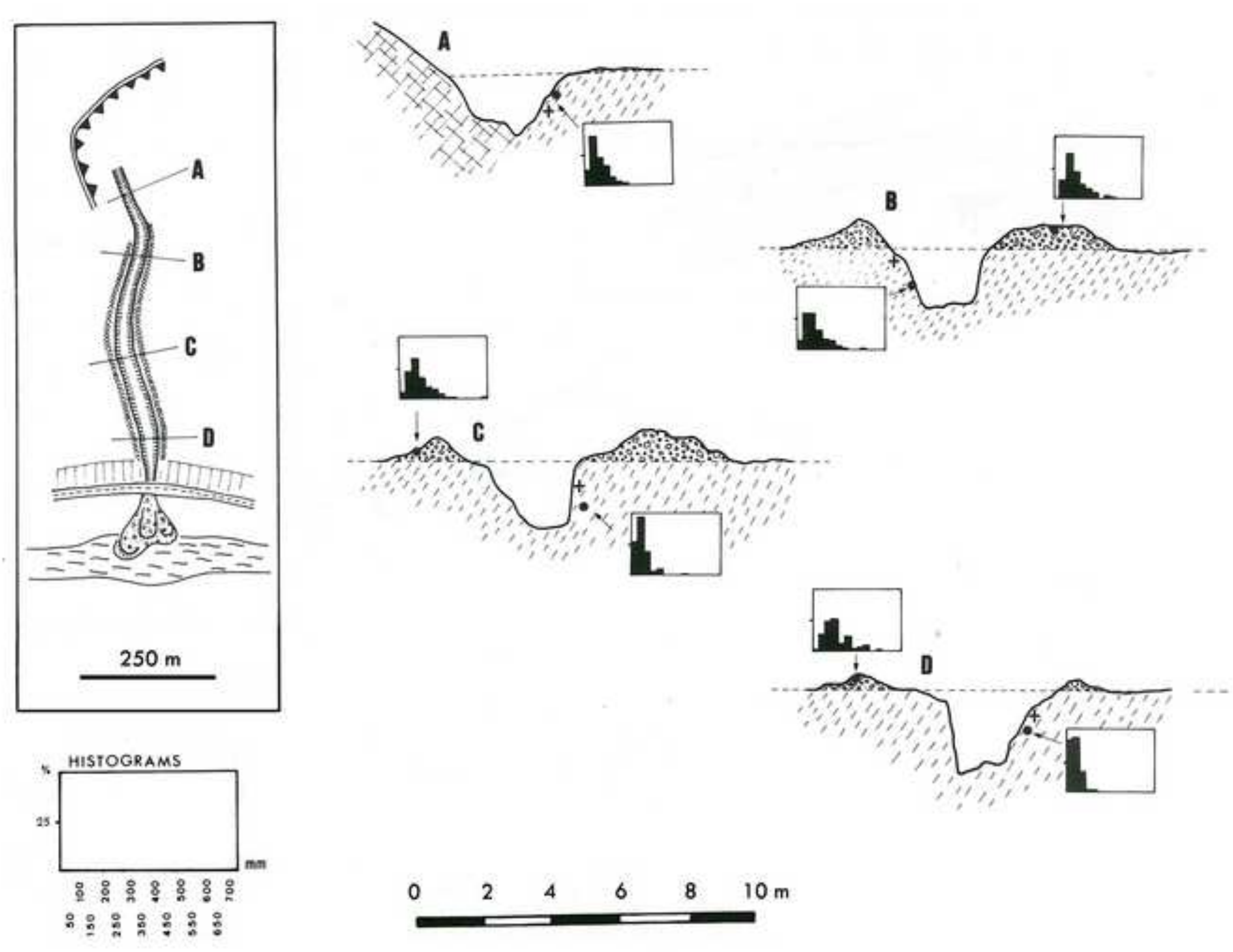


Figure7


A
B
C
D
250 m
HISTOGRAMS
%
25
mm
100
200
300
400
500
600
700
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350
450
550
650
A
B
C
D
0
2
4
6
8
10 m

Figure8

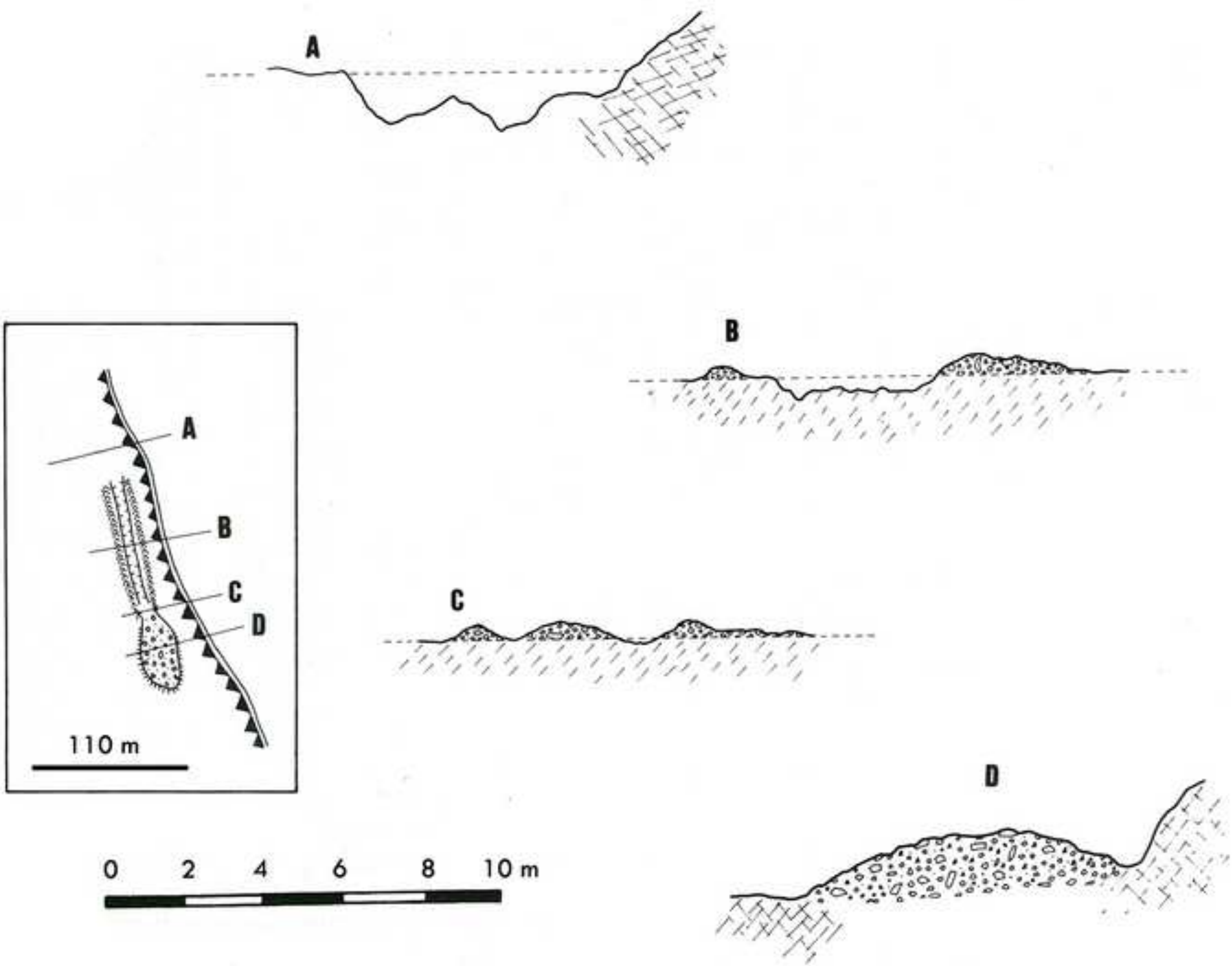

Figure9

Figure10

Figure11