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DEBRIS FLOWS SUBSEQUENT TO A FOREST FIRE IN THE NAJERILLA RIVER VALLEY (IBERIAN SYSTEM, SPAIN) [1]

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SUMMARY.— The authors study the main characteristics of the debris flows triggered in the Najerilla river valley after a wildfire. They comment on the importance of vegetation cover destruction and the role of topography and geomorphology: steep slopes, the presence of a concavity upslope of the scar, the low plasticity index of the fine matrix and the stroke of concentrated water against the slope deposits are factors that explain the onset of these mass movements.

RESUMEN.— Incendio forestal y coladas de piedras en en valle del Najerilla (Sistema Ibérico, España). *Se estudian las características principales de las coladas de piedras formadas en el valle del Najerilla después de un incendio forestal. Se concluye la importancia de la destrucción de la cubierta vegetal y el papel de la topografía y geomorfología: fuertes pendientes, la presencia de una concavidad aguas arriba de la cicatriz, el bajo límite de plasticidad de la matriz fina y el choque del agua concentrada contra el depósito de la ladera son factores que explican el inicio de estos movimientos en masa.*

RESUME.— Incendie forestier et laves torrentielles dans la vallée du Najerilla (Système Ibérique, Espagne). *On étude les principales charactéristiques des coulées de pierres formées dans la vallée du Najerilla à la suite d'un incendie forestier. On déduit l'importance de la destruction de la couverte végétale et le rôle de la topographie et geómorphologie: pentes raides, la présence d'une concavité en amont de la cicatrice, le bas limite de plasticité de la matrice fine et le choc de l'eau concentrée contre le dépot de versant sont les facteurs qu'expliquent le débout de ces mouvements en masse.*

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From the 15th to the 18th of August, 1986, a forest fire took place in the high Valley of the Najerilla River (Sierra de la Demanda, Iberian System, N. Spain), that affected more than 1.000 Ha. Small holm oak groves, oak groves and, especially, brush hillslopes were totally burnt. Several days after, on september 11th, a local storm struck the burnt area, with several geomorphological consequences. The ravines discharged great quantities of sediment into the main river, the Najerilla, and originated small but significative alluvial fans; moreover, local mass movements developed in a very stable mountainous area (ARNAEZ, 1987; GARCÍA-RUIZ, *et al.*, 1987).

The purpose of this paper is to define the main characteristics of these mass movements, to establish differences among them and to explain the physiographic and pluviometric context in which they have originated.

1. The study area

The high valley of the Najerilla river is located in the Sierra de la Demanda, a paleozoic massif —rejuvenated by the alpine cycle— in the northwestern sector of the Iberian System (fig. 1). The main divide, around 1900-2100 m. a.s.l., guards remains of old erosion surfaces from which straight slopes go down to the channels. Quartzites, slates, schists and sandstones are the more prevailing types of rocks. Slopes are covered by a deep mantle of screes, only partially active over 1800 m. a.s.l. Such screes have an important role in the hydromorphological behaviour of the massif: snowmelt and rain waters easily infiltrate in such a manner that overland flow lack importance. Almost all the water infiltrates and only close to the villages can one find important erosion processes (ARNAEZ, 1987; ARNAEZ & GARCÍA-RUIZ, 1984). Very local mass movements (associated with faults or morainic fronts), rills and active headwaters of ravines are the only problems of erosion in the Sierra de la Demanda. Around the divides some periglacial processes (terracettes, block fields, stone lobes) are still active (ARNAEZ, 1985).

Brush is the main vegetal formation (50 % of the total surface in the high Najerilla). *Rosa canina, Crataegus monogyna, Prunus spinosa,* acompanied by *Cytisus scoparius* and *Erica arborea* are the prevailing species. The most representative forestal species are oak, beech-trees and mountainous evergreen oaks.

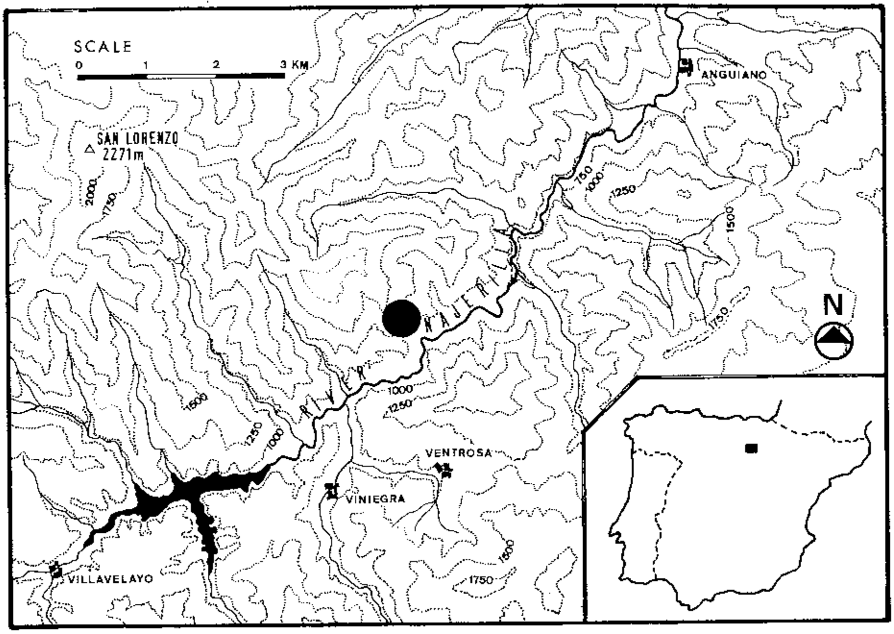


Figure 1. The study area. *(Area de estudio).*

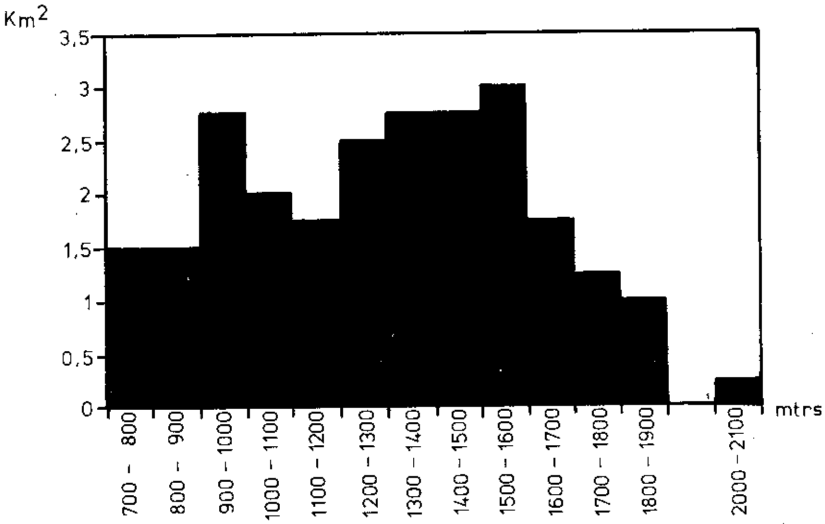


Figure 2. Distribution of the altitudes in the study area. *(Distribución de altitudes en el área de estudio).*

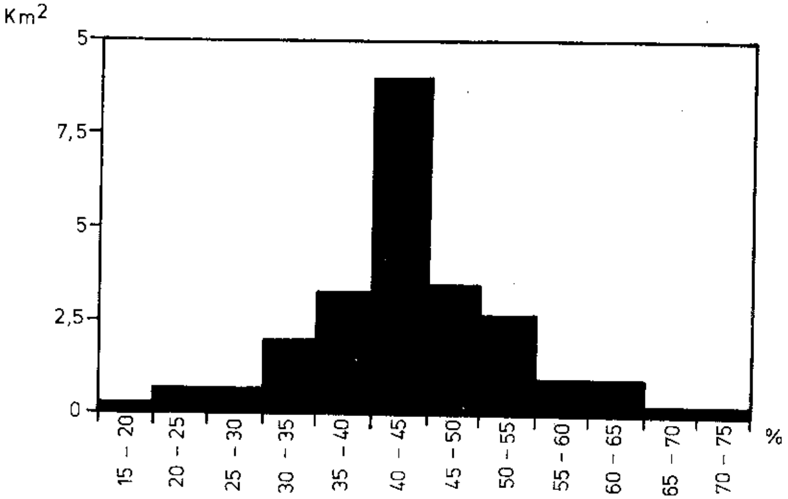


Figure 3. Distribution of the gradients in the study area. *(Distribución de pendientes en el área de estudio).*

The area affected by the studied mass movements range between 800 and 2000 m. a.s.l., with very steep slopes. Almost 40 % of the surface is around 40-45 % of gradient (fig. 2 and 3). Not all the burnt surface has had geomorphological problems after the fire. Problems have concentrated in a small sector on the left margin of the Najerilla river (fig. 4), though the physical features of the territory are very similar in all of the burnt area.

2. Methods

In each studied mass movement several topographic cross profiles were realized from the head to the front. Samples of the fine matrix were taken and Atterberg's limits and the plasticity index were obtained. Finally, coinciding with the cross profiles, the longest axis of 100 pieces of gravel was measured, according to the WOLMAN's (1954) sampling system. In such a manner, we have the gravel size classification in several points of each mass movement. In all cases in which it was possible, the talus screes —in which such processes have their sediment source— were also sampled.

3. The storm of september, 11, 1986

Three weeks after the forest fire a very local storm fell on the southeastern hillslopes of the San Lorenzo massif. This meteorological phenomenon coincided with the advance of a cold front that also originated isolated storms in other areas of the Iberian System. Unfortunately there is no reliable pluviometric records. Valvanera rain-gauge, 4 Km northward from the site of occurrence of mass movements, recorded 13 mm. But undoubtedly the rain that had fallen in some points was much greater. The statistical analysis of maximal precipitations in September over 35 years on the Valvanera rain-gauge points out that these 13 mm are absolutely normal for a period of 24 hours. Gamma distribution allows us to conclude that a maximal precipitation of 15 mm or less has a 50 % probability of falling in September. Rains of similar or even superior volume have fallen after 11th September 1986, nevertheless they have not originated any outstanding geomorphological phenomenon.

A very indirect way of calculating rain intensity is from the peak-flows of some ravines. Near the mouth of the Pítare ravine we measured the parameters necessary to apply Manning's equation (cross section, channel gradient and Kutter's coefficient of rugosity). The height reached by stream water was deduced from the position of several stems expelled by the flood. A peak-flow of 157,6 m^3/s^{-1} is obtained. The minimal rain intensity to produce this peak flow should correspond to a rainstorm of equal or superior duration than the *time of concentration* and for a runoff coefficient equal to 1. In such conditions, being the basin surface of 2,7 Kms^2, one could calculate an intensity of 3,5 mm per minute. This discharge is surely overstimated owing to the great amount of sediment load during the peak flow, the waves that arrange the floating stems in strange positions and the change of shape of the channel during the flood. This figure comprehends the expected intensities during short periods and for small surfaces (see, for example, JENNINGS, 1950; SHAN & AMMERMAN, 1947. See also the data of DUNNE & LEOPOLD, 1978). The rainfall intensity calculated (3,5 mm per minute) is the lowest to produce the peak flow. Its duration is at least that of the time of concentration, that to a basin of 3.150 m length and a difference of level of 1.060 m, is equal to 0,244 hours (i.e., 15 minutes). *In such a time, the minimal rainfall to produce the peak flow is then, 52 mm.* If we apply the CAINE (1980) formula:

$$I = 14.82\ D^{-0.39}$$

where I is the rainfall intensity (mm hr^{-1});
D is the duration of rainfall (hr),

we obtain a result of I = 14.28 mm hr^{-1}. *This figure is considered, for the conditions of the studied basin, as the threshold to trigger the debris flows.* This threshold is clearly beneath the minimal rainfall calculated. The figures are only orientative but the differences between both parameters is so great that we can conclude its signification.

In the main river, the Najerilla, the rainstorm had little significance. At the Anguiano gauge-station, the day 10, before the rainstorm, discharge reached 10.95 m^3 / s^{-1} and the day 11, 11.40 m^3 / s^{-1}. These figures mean that the rainstorm had a very local character.

4. Geomorphological consequences

As a consequence of the storm, important sediment transport was produced in the slopes. Several ravines quickly increased their discharge and carried out sediments from their headwaters, originating small alluvial fans at the mouth. Moreover, in a sector of the burnt area four mass movements of great size were triggered. They can be classified as debris flows, after VARNES's (1978) classification, since they are integrated by heterometric material, between which coarse ones predominate (gravels, cobbles and blocks), spatially distributed at random in a fine-grained matrix. LOWE (1982) emphasizes that the debris flows are subaequous sediment gravity flows that behave in a plastic manner, moving downslope as a confined slurry. MIDRIAK (1984) refers to debris flows as an interstage between gravitational and fluvial-gravitational phenomena. Debris flows begin in a scar or crown and have an enlogated shape in the sense of the slope, sometimes with a more or less incissed central channel. The deposit has almost always a frontal snout or final toe (sometimes with concentric constructional ridges) and lateral deposits (levees), as a result of the strength, separated by a depressive zone or by the mentioned incision, as described by SHARP (1942). A more detailed study of their general characteristics can be found in INNES (1983), COSTA (1984), JOHNSON & RODINE (1984) and CROZIER (1984 and 1986). Other terms used to refer to this phenomenon are debris avalanches (CROZIER, 1973; CAMPBEL, 1951), catastrofic debris flows (HUTCHINSON, 1977), etc. Even CURRY (1966) uses the term mudflow to refer to a deposit with prevailing coarse gravels. Generally, debris flows have been related to extraordinary rainstorms (WILIAMS & GUY, 1973; CURRY, 1966; TEMPLE & RAPP, 1972;

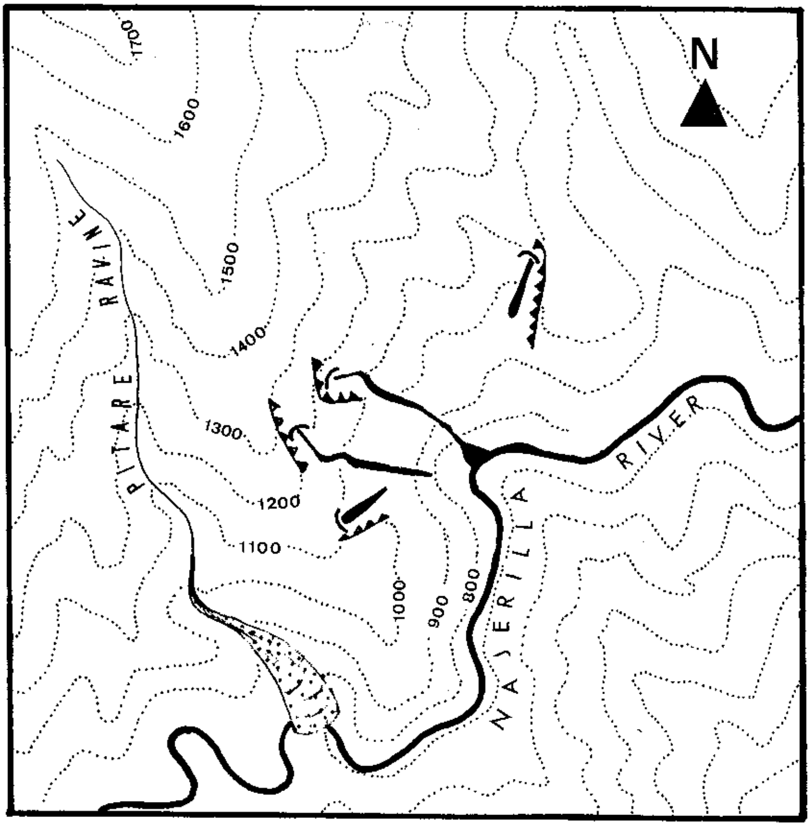


Figure 4. Site location of the mass movements in the Najerilla basin. *(Localización de los movientos en masa en la cuenca del Najerilla).*

Johnson & Rodine, 1984; Okuda *et al.,* 1980). All over the world they have been pointed out in many different enviroments (see Caine, 1980). Several examples can be quoted in Spain, especially in the Pyrenees (García-Ruiz & Puigdefábregas, 1984; Corominas & Alonso, 1984; Bru *et al.,* 1984; Clotet & Gallart, 1984). In all cases the triggering threshold seems to be related not only to the total depth of rainfall but also to rainfall intensity (Starkel, 1979).

All the cases have a short run; the longest debris flow measures aproximately 500 mts, and the shortest one, 200 mts. One of them is almost a tributary of the other, though they do not inter-connect. In all cases they are located in concave, very steep slopes, under quartzite scarps. It is very important to consider that these debris flows settle in

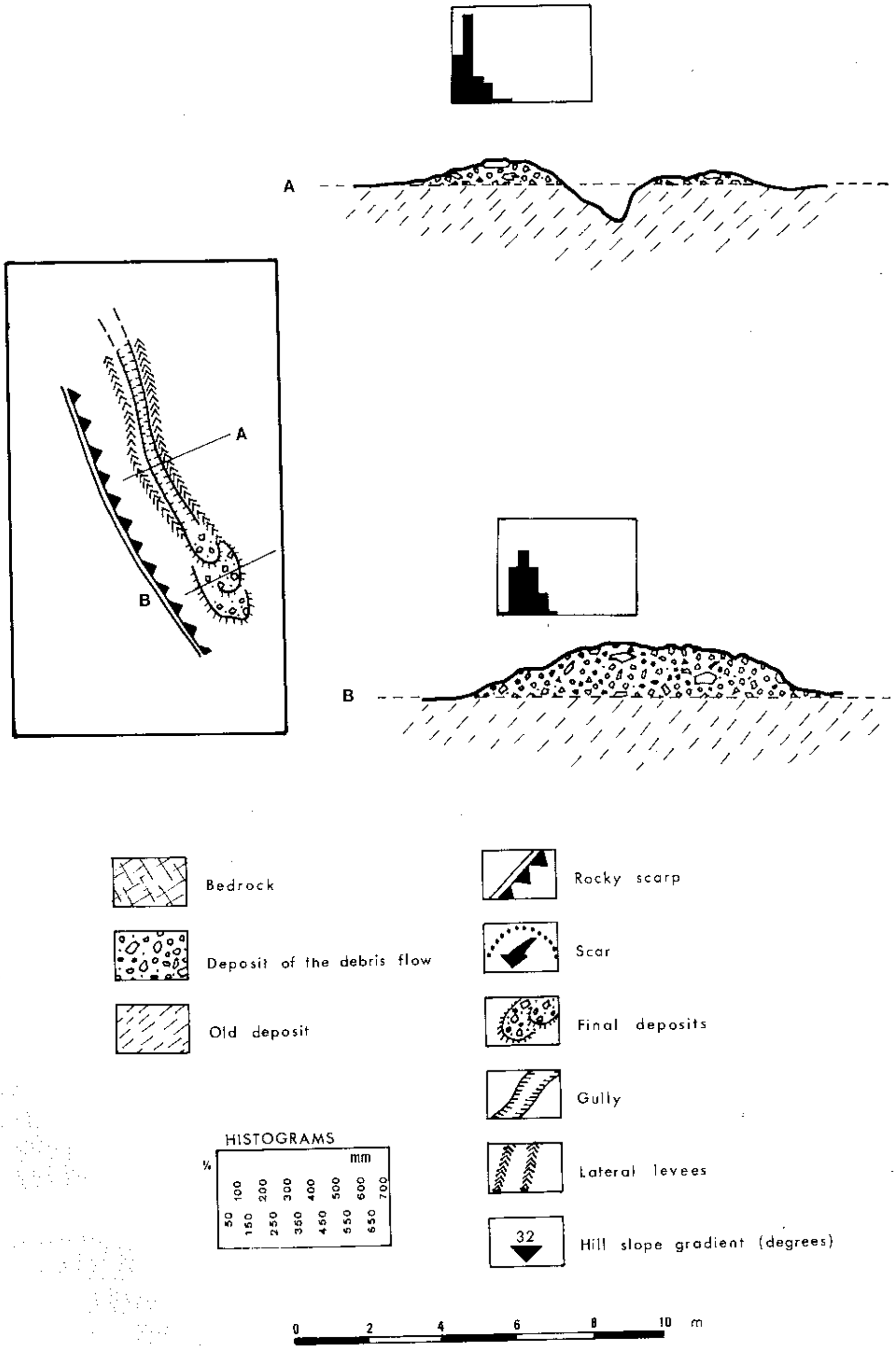


Figure 5. Debris flow F-1, with transversal profiles and histograms of particle size distribution. *(Colada de piedras F-1, con perfiles transversales e histogramas del tamaño de los sedimentos).*

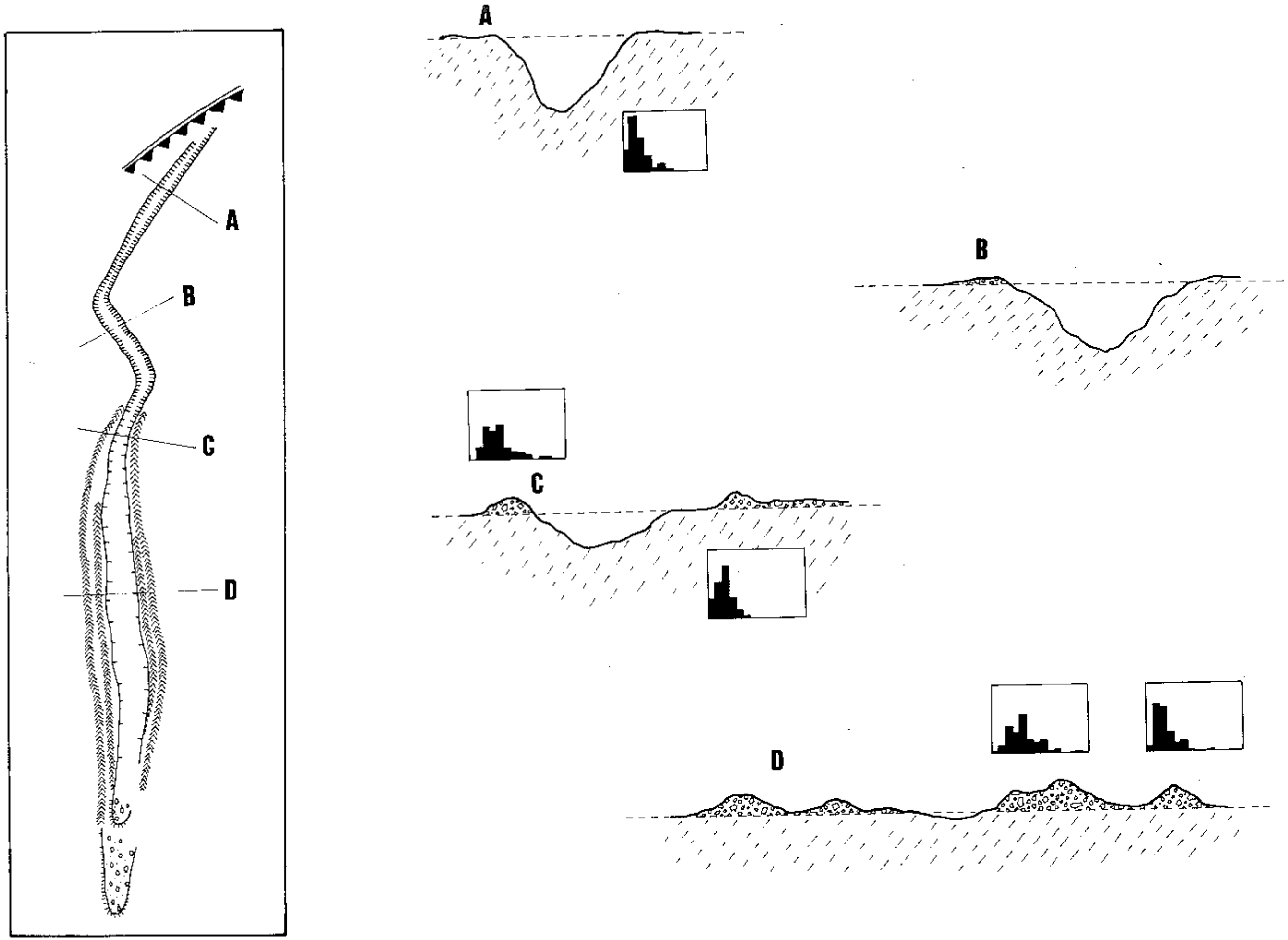


Figure 6. Debris flow F-2. See legend on fig. 5. *(Colada de piedras F-2. Véase la leyenda en la fig. 5).*

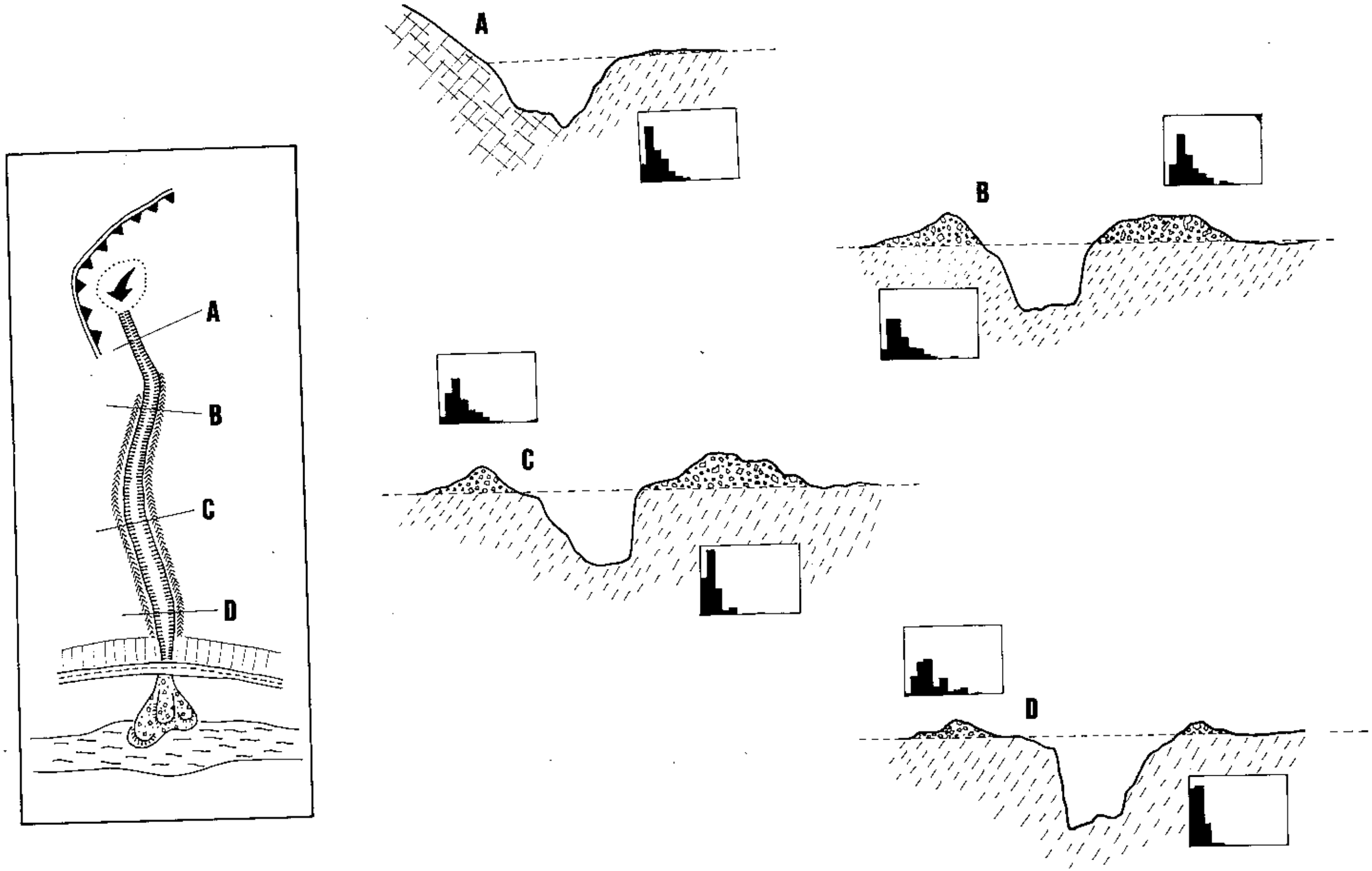


Figure 7. Debris flow F-3. See legend on fig. 5. *(Colada de piedras F-3. Véase la leyenda en la fig. 5).*

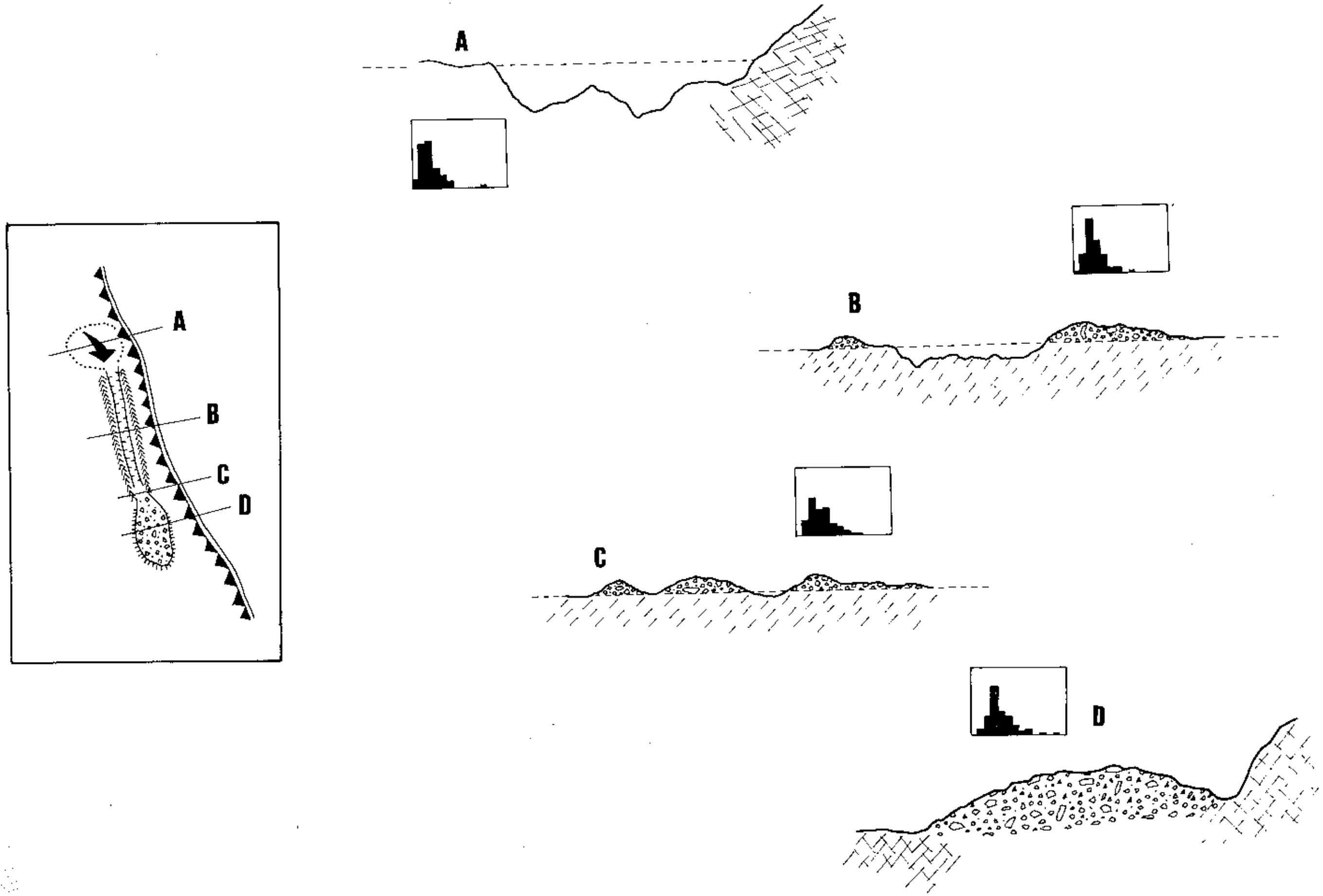


Figure 8. Debris flow F-4. See legend on fig. 5. *(Colada de piedras F-4. Véase la leyenda en la fig. 5).*

slopes with abandoned fields, at least in their lower sector. Some of the debris flows (for example, F-4) cover stone terraces, which indicates that they were considered as stable slopes by farmers.

Figs. 5, 6, 7 and 8 show plan and several transversal profiles of every debris flow and the histograms of sediment size —both those removed after the forest fire and those located under the debris flows, which correspond to the relatively old hillslope deposits. The latter, in which the niche is settled, have constituted the major source of the crawled materials. The accumulation of sediments begins almost inmediately downslope from the scar, especially in debris flows F-1 and F-2; F-3 begin with a gully, without accumulation, so we can deduce that debris flow velocity was initially too high to allow sedimentation.

TABLE 1

Particle size distribution of the fine matrix in the scars (%)

	F-1	*F-2*	*F-3*	*F-4*
Clay	20,5	8,1	0,4	14,3
Fine silt	17,7	13,7	14,6	22,0
Coarse silt	7,2	8,1	7,7	11,9
Sands	54,6	70,1	78,1	51,7
Coarse sands	26,9	44,3	44,3	46,3

Table 1 shows the grain size distribution of the fine matrix in the sediment source. In the scar, debris flows F-2 and F-3 have a great proportion of sand (more than 70 % in the first case and nearly 80 % in the second), so we can include these samples in a loamy-sandy category. Debris F-1 and F-4 have also a lot of sand (more than 50 %), though they can be classified as loamy ones. Every sample has abundant coarse sand (above all F-2, F-3 and F-4) and is hardly clayey, especially F-3. Low clay content seems to be normal in all natural debris flows (INNES, 1983). This grain size distribution proves that, in origin, they are little biochemically weathered materials, produced by physical weathering, as a subproduct of frozen-thaw processes. This is why the sediment source of debris flow is extremely poorly sorted, a common feature to all debris flows.

These matrix characteristics perform a very important role in slope stability. Atterberg's limits have been calculated and also the plasticity index. Nevertheless, in debris F-1 and F-3 such parameters could not be obtained since the sample liquified inmediately. In F-2 and F-4 the plasticity indexes are very low (8 and 7 respectively), that's to say, once the plastic limit is reached, the deposit hardly needs water to reach the liquidity limit. The importance of sand and the scarcity of clays explain the instability of the material in presence of water. Of course, the matrix constitutes aproximately only 20 per cent of the deposit and so it performs a limited role in its stability, more linked to problems of internal friction of the gravels and to repose angles.

Debris flow F-1 has upper and middle sectors with lateral deposits, that leaves a central depressive area. In the lower sector, the snout constitutes a sucession of lobes —of great downslope size—, as successive waves. The frontal part is 10,5 m wide, with a thickness of 1,42 m It is a somewhat complex lobe, with a convex cross profile. Materials are notably coarser in the frontal snout than in the middle sector, as the data and histograms show.

F-2 is very similar to F-1, but with more stumped frontal lobes. Near the front one can see a twofold pattern of lateral deposits, corresponding to two successive waves of debris flows. Two frontal lobes confirm the existence of a double flow. In the widest sector, the lateral deposits are separated by 19,5 m, the greatest distance in all the studied cases.

F-3 is framed by a well defined drainage line, with small deposits, such as pauldrows (see fig. 7). In the front, it leaves a great lobe integrated by superposed debris flows that were able to block the Najerilla river channel. It is not a new incision, since it can be seen in the aerial photograph of 1978, and serves as drainage line to a small basin. The channel is more than 3 m deep and more than 5 m wide, and given the position of the lateral deposits, we can suppose that it was completely covered by the debris flow. It is, then, a mass movement that profites a previously established line. No deposits have remained in the channel, surely owing to underloaded flood waters following the main debris waves. JOHNSON & RODINE (1984) point out that medial deposits are rarely preserved. In this sense, PIERSON (1986) has demonstrated that hyperconcentrated flow towards the end of the flow tail can originate bank undercutting and channel widening, once the debris flow has passed. The rocky bed has abundant signs of impact and clasting provoked by the violent passage of materials.

In the front three lobes can be distinguished, arranging a whole deposit of 33 m width. The longitudinal prolife shows the existence of tipical grades (steps) of debris flows, that advanced in successive waves. Also in this flow one can see a progressive increase of the gravel size from the upper part to the toe, unlike the original deposit.

The debris flow F-4 is the more simple one. It has a unique tongue of 12 m width and 2 m depth in its middle part. In its final stretch it gives a very convex cross profile, banished by some rocky outcrops that have impeded a greater lateral expansion. Gravels also increase in size to the snout. From the toe a small gully merges, as a consequence of the channelization of the runoff produced by the debris flow.

The spatial organization of gravel size allows us to establish

Photo 1. Debris flows F-1 and F-2. F-2 surges just under a cliff and has a scree deposit as a source of materials.

Photo 2. Alluvial fan of the Pítare ravine. It is a fresh deposit originated during the storm.

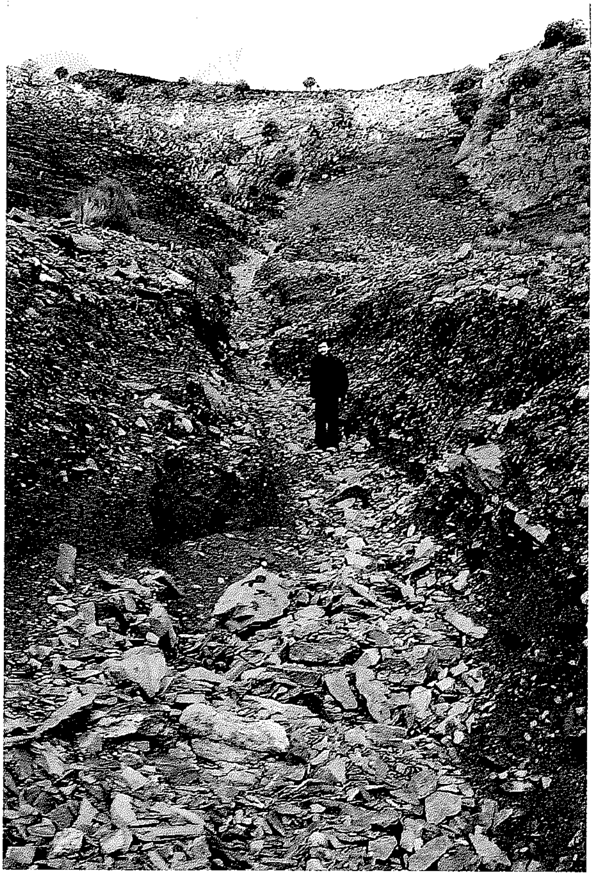
important differences beween the removed deposits (debris flows) and the older talus screes. We must consider that the sampling method ought to be responsible for part of such differences, because the stone size at the surface could not be representative of the total deposit. Thus, debris flows, as a mobilized deposit, are affected by the "sieve effect" and show greater gravels and cobbles on the surface than in the interior. In part, this is the reason why the debris flows have a greater mean stone size than the original talus screes, located inmediately beneath. This phenomenon is well appreciated in F-2 and F-3. In F-2, near the scar, the original scree deposit has a mean size of 113,5 mm, whilst the materials of the levee reach 207,7 mm; in the middle, the talus deposit has a mean size of 79,2 mm and in the debris flow the size is 212 mm. In F-3 the talus deposit has in the middle sector a mean gravel size of 86 mm, and the levee of 157,6 mm; in the lower part, the sizes are respectively 67,8 and 202, 6 mm. The differences are, then, very outstanding and tend to increase in the lower part of the slope. Nevertheless it is not this difference in which we are interested, but in the downslope tendency proved by every deposit.

From head to foot in the slope, the evolution of the mean stone size shows a contrary tendency in the old deposit and in the debris flows. In F-2 and F-3, the debris flows allow us a better confronted study, the mean size of the talus scree decreases progressively downslope, whilst it increases in the debris flow. The debris flows F-1 and F-4 show the same tendency of downslope increase, though we could not study there the old deposit.

5. Discussion and conclusions

A rainstorm several days after a wildfire provoked the triggering of important geomorphologhical processes in the Sierra de la Demanda (Iberian System, Spain). Some ravines apported a great quantity of sediment and a new alluvial fan was developed; at several points slopes were unstabilized, causing mass movements of debris flow type. On such slopes there is not any evidence of similar geomorphological processes. Older deposits —that have been described by ARNAEZ (1987) in many other points of the Sierra de la Demanda— are gravity deposits, but the spatial organization of gravel size obliges one to think of the role of pipkrakes and of non-concentrated overland flow. Grain size classification from head to foot is very different to that of the studied debris flows. We can, then, conclude that they are two different processes.

On the other hand, we must to take into account that the debris flows reach, in their final stretch, old cultivated fields which are already abandoned; this means that such mass movements were unknown in



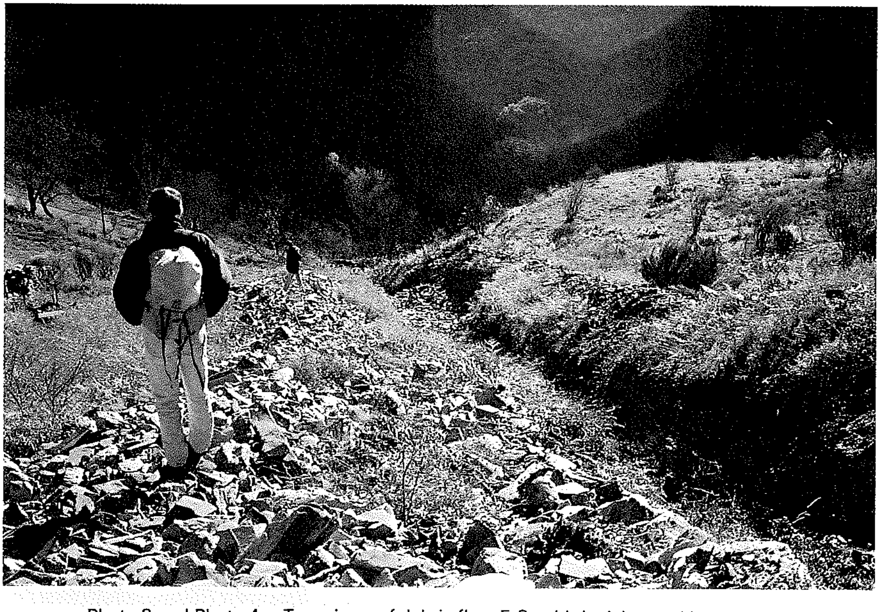


Photo 3 and Photo 4. Two views of debris flow F-3, with incision and lateral levees.

these slopes. However, similar examples —though of lesser size— have been identified between 1.800 and 2.200 m. a.s.l., on the southern slopes of the San Lorenzo massif, very near the studied area. But there the conditions are somewhat different: vegetation is very scattered and the soil has a more abundant fine clayey matrix. During snowmelt the water content is very high: very rectilineous debris flows of small scars but of long run develop small lateral deposits and snouts.

The forest fire has had indoubtedly some responsibility in the beginning of the debris flows. The intense rainstorms of September, 11th, 1986, fell on unprotected slopes, in which the role of interception was very limited; moreover, some authors (i.e., DE BANO, 1969) have demonstrated that intense heat during wildfires originates a thin impervious crust on soil surface. JOHNSON & RODINE (1984) and CLEVELAND (1973) insist in that an intense rainstorm after a fire can cause dense rill and gully networks and, locally, in steep sectors, debris flows, as also has been pointed out by MIDRIAK (1984) in the Czechoslovak Carpathians. CHINEN (1987) shows that, after a forest fire, sediment yield is very important during the first year and drastically reduces onward. In this sense, several authors have emphasized the close relation between deforestation and debris flows (SWANSTON, 1976; BLACWELDER, 1948). Nevertheless, in the case under study, the volume of precipitation seems to be enough to produce the debris flows, as we have demonstrated from the calculation of the lowest rainfall intensity, the time of concentration and the CAINE equation. These figures prove that the rainstorm is the main reason of the triggering of the studied mass movements and of the new alluvial fan of the Pítare ravine, though, no doubt, the fire contributed to its formation, owing to the absence of vegetation.

Also, several factors explain the origin of the studied debris flows under hard rain conditions. All of them are in very steep slopes —a factor considered of great importance (BAILEY & RICE, 1969; BRUNSDEN, 1979)— and their sediment source has been non consolidated talus screes, with a heterometric mixture of gravels and cobbles in a scanty fine matrix (BLACKWELDER, 1928); the latter, moreover, has a very low plasticity index and soon liquifies. In the mayority of cases, the increase of interstitial porewater pressure is followed by decrease of friction angle, and cohesion is reduced as the amount of interstitial water increases (CROZIER, 1986). In materials with low liquid limits, liquefaction may occur quickly, especially if vegetation does not frame a strong and coherent root mat (OWEN, 1981). We must add that debris flows have begun in concave areas, where shallow and subsuperficial runoff tends to concentrate, and that in some cases a relatively well developed gully was uspslope. VAN STEIJN, *et al.,* (1988) emphasize the importance of gully systems situated upslope from the present flow tracks, able to apport great quantities of water and sediments instantaneously.

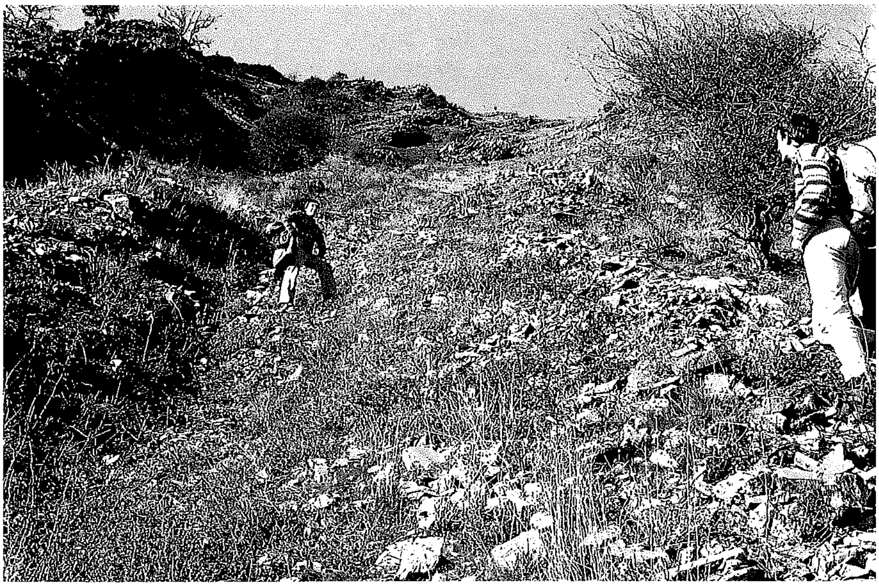


Photo 5. Debris flow F-2, with lateral levees. No incision is developed.

Photo 6. Frontal lobe of the debris flow F-5. It has a convexe shape and is constituted by coarse deposits, mainly at the front.

Moreover the debris flow scars are dominated by quartzite scarps, above which the water concentrated in the concavities flowed. So the process in very similar to that pointed out by JOHNSON & RODINE (1984) and by FRIXELL & HORBERT (1943): the heterometric talus deposit is practically saturated by intense rainstorms and receives the rough impact of water coming from upslope, travelling at concentrated and high speeds. The impact, originates the dispersion of large masses of talus screes and the origin of debris flows. The so-called "firehose effect" by JOHNSON & RODINE (1984) needs very special topographical conditions: steep slopes, concavity and gully upslope of the talus deposit and a scarp originating a small waterfall that strikes the talus.

The spatial organization of gravels is controversial with some authors. VAN STEIJN *et al.,* (1988) and CROZIER (1984) express the progressive and gentle decline of mean size with distance from the source of sediments. This does not agree with our field data, because the mean size increases downslope and reaches its maximal value at the toe of the debris flow. Perhaps the pronounced gradient and the great stone size of our studied area explain the important role carried out by gravity force. On the contrary, our results agree with other authors, such as PIERSON (1986), JOHNSON & RODINE (1984) and CURRY (1966), who point out the location of the largest boulders near the outer edge of the front. We must to take into account, according to JOHNSON & RODINE (1984), that in a debris flow the blocks are not abandonned by incompetence, but due to the flux stop; the viscosity of the deposit allows the displacement of coarse blocks and cobbles, without a selection in size throughout the distance. It is a phenomenon similar to that of the very torrential rivers, in which important quantities of sediments move as a cloud of stones, almost without any process of sorting (LEOPOLD *et al.,* 1964; GARCÍA-RUIZ, *et al.,* 1987).

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