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RECONSTRUCTION OF MAGNITUDE AND FREQUENCY OF DEBRIS FLOWS IN THE REBAIXADER TORRENT (EASTERN PYRENEES, SPAIN) BY DENDROGEOMORPHOLOGICAL ANALYSIS

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ABSTRACT

Occurrence of debris flows has received little attention in the Pyrenees, probably due to the small risk shown by most of the debris-flow prone sites in this mountain range. Nevertheless, the event of Biescas (which occurred in August 1996 and that caused 87 casualties) demonstrates the existence of high risk spots in the region.

Historical data on debris flow occurrence are usually scarce or lacking in the Pyrenees, as in many mountain ranges. This makes difficult the determination of their frequency. Dendrogeomorphological techniques have shown their efficiency in reconstructing temporal series of debrisflow events from which frequency can be assessed. The determination of magnitude of an historic event can be done by distinguishing its deposits, but this is not a trivial task in debris fans that accumulate deposits corresponding to consecutive debris flows, especially if only a conventional geomorphological analysis is carried out. In catchments where debris-flow frequency is moderate to high (i.e. return period of several years) deposits corresponding to each event (event deposits) are identifiable using a set of relative dating criteria, like cross-cutting relationship, size and cover percentage of lichens on blocks, forest density and size of trees colonizing the deposits. The event deposits can be mapped and, subsequently, trees damaged by the flows sampled for dating of events. This approach was tested in a Pyrenean catchment where debris flows develop in periglacial deposits and under a submediterranean climate (Tordò creek). Now the method has successfully been extended to assess the frequency-magnitude relationship of debris flows in a different setting, the Rebaixader creek, in which the mobilizedmaterial is a glacial till and the local climate is a high mountain one but with mediterranean influence. Seven event deposits have been mapped and dated in the Rebaixader creek, corresponding to debris-flows events occurred during the last eighty years, involving a depositional area 90,000 m^2. A magnitude-frequency relationship was prepared for the site and is compared to that of the Tordó creek.

Key words: *debris flows, dendrochronology, relative dating, frequency, magnitude*

INTRODUCTION

Mass movements are the manifestation of physical erosion's processes actively shaping landscape. Debris-flow occurrence in stream channels has been reported in numerous mountainous environments (Coussot & Meunier, 1996; Jakob, 2005) including the Eastern Pyrenees (Hürlimann *et alii*, 2003; Portilla *et alii*, 2010). Together with the vivacious remembrance of the 1996 Biescas debris flow (camping site hit and 87 casualties suffered; Alcoverro *et alii*, 1999), it pledges for the existence of high-risk spots in the region.

Debris flows leave traces in the landscape and on vegetation: landslide scars, channels, depositional areas, lateral levees, bent trees, wounded trees among others. Thanks to dendrogeochronological techniques, it is possible to date the traces left on trees cohorts growing on the fan. Past studies have shown the adequacy of such techniques when debris flows are involved (Stoffel *et alii*, 2006; Stoffel & Bollschweiler, 2008; Bollschweiler *et alii*., 2008; Corominas & Moya, 2010).

Few attempts have been made so far in the estimation of the magnitude of debris-flow events using dendrogeomorphology. One approach combining tree-ring and relative dating was tested in a Pyrenean catchment where debris flows develop in periglacial deposits and accumulate in a valley bottom (Tordò creek, Eastern Pyrenees). Here, the method is extended to another Pyrenean site, the Rebaixader creek, in order to start a regional study of magnitude-frequency of debris flows and to check the method in a different setting (a debris fan).

STUDY AREA

Rebaixader torrent is a tributary of the Noguera Ribagorçanariver and lies in the high reach of the basin, about 10 km south of the atlantic-mediterranean water divide (Fig. 1). The bedrock consists of the Paleozoic meta-sedimentary rocks of the Axial Zone of the Pyrenees, which were folded during the Hercynian and Alpin orogenesis. Tills overtopping the bedrock were deposited during the Upper Pleistocene by a glacier that occupied the Noguera Ribagorçana valley (Vilaplana, 1983). Deglaciation resulted in destabilization of the steep slopes developed during the Last Glacial cycle, giving rise to landslide activitiy.

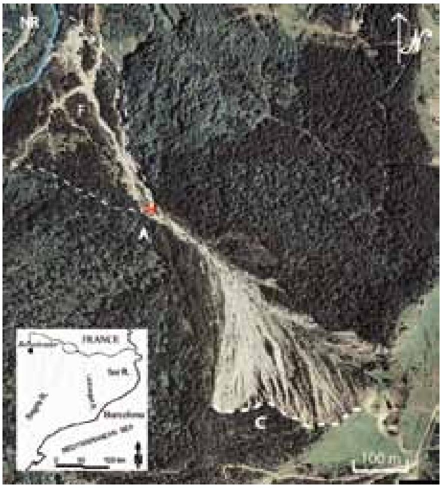

Fig. 1 - Aerial view of the Rebaixader creek. The inset shows the location of the site. C: head zone; F: debris fan; A : fan apex; NR: river Noguera Ribagorçana

.The catchment of Rebaixader lies between 2479 and 1225 meters above sea level (m asl). Its catchment's area has an extent o 0.7 km2, and its length 2.6 km. The mean slope of the catchment is 28 degrees. The head zone has a semi-circular scar culminating at 1725 m asl (Fig. 1). The debris fan has the apex at 1325 m asl and the bottom at 1225 m asl, in the confluence with the river Noguera Ribagorçana. The channel linking the source zone and the fan is 630 m long. The fan has a radius of 370 m, an area of 0.082 km^2 and a mean slope just over 15 degrees; this last value may seem intriguingly high for an alluvial fan but D'Agostino *et alii* (2010) report even greater values of depositional areas (fans) mean slope. The fan was built up by debris flows and displays a complex ensemble of deposits, which are mostly colonised by a forest of Pinus Sylvestris. Rebaixader has recently been monitored (summer 2010). Geophones and an ultrasonic device, which have been set up to control occurrence and discharge of debris flows, and a meteorological station to control rainfall conditions, are also currently operating (Hürlimann *et alii*., 2011)

. No historical data on past events having affected the study area have been encountered, safe a debris-flow event recognised in 1963 to have developed in an adjacent catchment (Brocal, 1984).

METHODS DETERMINING THE DEBRIS-FLOW MAGNITUDE

The magnitude of debris flows is conventionally expressed as its volume of deposition. However, assessing the volume of past debris flows from field work can prove to be complicated. Past studies have emphasized the relationship between volume and area of debris-flow deposits (Iverson *et alìi*, 1998; Berti & Simoni, 2007; Scheidl & Rickenmann, 2009). The magnitude can thus be assessed by delimiting the surficial extent of the deposit and extrapolating to an estimate of the volume deposited.

Nevertheless, at sites where debris flows are recurrent, as on a debris cone, new debris-flow events may remove evidences of earlier ones by eroding or overlapping them. As a consequence, several parts of a debris-flow deposit can be found at present separated by younger deposits or by a channel scoured by a more recent event. These remnants should be identified as corresponding o do this, sediments deposited by debris flows were differentiated using relative dating criteria, and were grouped into relative-age classes and, finally, assembled by correlation in depositional units. The term depositional unit is used for a set of deposits included in a relative-age class and can be regarded as accumulated by a debris-flow event. The definition of the depositional units is indispensable for estimating debris-flow magnitude and age (Corominas & Moya, 2010) even though constraint inherent to field works can render it time-consuming.

At the Rebaixader creek, the fan is the place of preferential deposition of the debris flows developed in the site. A series of criteria has been used in order to distinguish between different depositional units (DU) accounting for its development: maximum size of trees (diameter and height), lichen's cover on boulders making up the DU and cross-cutting relationships (i.e. in-channel deposits are younger than terrace deposits). Each depositional has developed different cohorts of trees and lichen development covering the fan to different extents (Fig. 2).

In Rebaixader, assessing the size of past debris flows is rendered very difficult due to the superimposition of depositional units. The magnitude of debris flows is conventionally expressed in volume but can also be determined in terms of area of event deposits. The site dictated the use of area of deposits (of depositional units, more exactly) to express the debris-flow magnitude; this is because the low relief in the fan surface made very difficult the estimation of the deposits thicknesses.

FREQUENCY

Once the number and extent of the depositional units were determined for the site, the numerical dating was carried out by means of dendrochronology.

Two types of tree-ring dating elements were found at the site: trees wounded by debris flows and trees colonising the depositional unit's surface. Dating of wounds by counting the number of rings having straddled over the scar gives the number of years passed since the tree was injured, and, therefore allows an exact dating of debris flow occurrence (with an accuracy of a growing season). The age of trees colonising depositional units gave a minimum age of the corresponding debris-flow events. There is a time span between the new surface's formation and the

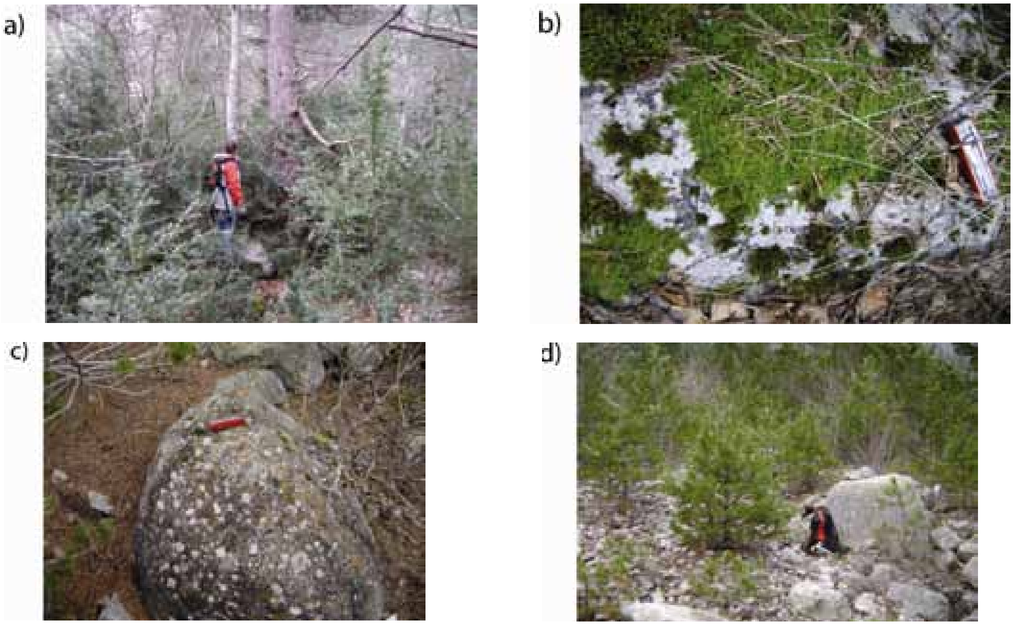

Fig. 2 - Examples of relative age characteristics shown by different depositional units in the Rebaixader debris fan. a) and b) show DU 7 trees and lichen assemblages; c) shows lichens for DU 5; d) exhibits trees as found on DU 3.

colonisation by trees. The time for colonizing a newly formed surface, ecesis time or colonization time gap, is highly variable and depends upon a wide variety of controlling factors (Schroder, 1978).

To obtain the age of colonising trees two techniques have been used, depending on the apparent age of the trees:

1) For old or mature trees, a core of the biggest (likely to represent the oldest) trees was extracted (45) and the rings counted. The minimum age for the event which produced the surface (in our case DU) is given by the germination date of the oldest tree.

2) For young trees, conifers younger than 30 years old, another technique (more direct and easily applicable) was used. It is based on the fact that the number of branch whorls of a young conifer indicates the tree age (Schweingruber, 1990; 371 young pines were dated by this method).

Obtaining the tree age form cores has several shortcomings. First, the sampling height should be as close to ground level as possible in order to hit the oldest tree-ring of the tree (e.g. Grissimo-Mayer, 2003). The higher the sampling height, the greater the number of tree-rings formed before the tree reaches this height. This is called the Sampling Height Growth Time (SHGT). A sampling height common for all trees is hardly achievable as it depends on the access to the tree. In this study sampling heights ranged from 0.5 to 1.4 metres. Second, cores may not reach the pith (which is the oldest part of a tree radius). Thus, results given by this technique are subject to approximations, as Schroder (1978) emphasized.

In order to get the most exact age, a series of corrections has been realised. When the pith was not hit and inner growth ring arcs were visible, the geometric model proposed in Duncan (1989) was used to estimate the number of rings between the last visible ring and the virtual pith. Details and limits of the method are not discussed here and can be found in the reference above. This method is not applicable to all cores as arcs are not always visible. 23 cores are concerned by the method. The colonization time gap (CTG) can be defined as including the Germination Lag Time (GLT) and the Breast Height Growth Time (BHGT) (following Pierson, 2007) or the Sampling Height Growth Time (SHGT) if the samples were taken close to the ground. Because the cores were sampled as close from the ground as possible, the BHGT is considered as null or small. The GLT is highly dependent of the local conditions, as mentioned above, and has not been studied for Pinus Sylvestris in the study site. Pierson (2007) found that for a mixed population of conifers, the GLT had a mean value of 6 years. Although this gap has only been taken as guidance for the Rebaixader creek, it was not applied to obtain tree ages.

A minimum age for each depositional unit was finally obtained after applying the age-corrections to samples and using the age of the oldest tree colonising the unit.

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RESULTS

DEBRIS FLOW DEPOSITIONAL UNITS AND MAGNITUDE

Using these different features, seven depositional units have been recognized on Rebaixader's fan. Below is their description:

- The first depositional unit recognised (DU 1) corresponds to the currently active channel. No vegetation is found and lichens have not covered boulders yet.
- DU 2 is made up of small trees scarcely distributed and its boulders are not colonised by lichens.
- DU 3 exhibits trees of medium size (up to human size) with an increase in the density, and boulders covered by lichens; coverage estimated to range from 5 to 10 %.
- DU 4's trees are between 2 and 3 meters high with a diameter varying between 5 to 10 centimetres. Boulders are covered with lichens (15-20%) and moss (scarcely).

To be noted is the accumulation of organic matter (twigs, spikes, leaves…) on the ground.

- DU 5 shows a dense cohort of trees with diameter closing 10 cm and as high as 4 meters. Very similar to DU 4, the difference resides in the assemblage of lichens found on the boulders. Lichens (white and yellow) cover 30-40 % of them, and moss less than 5%. Ground remains covered with organic matter.
- DU 6's trees exceed 4 m, and diameters range from 15 to 25 cm. Their density decreases compared to DU 5. The boulders are covered by 5-10 % of moss, the rest being almost entirely covered by both lichens. Organic matter is still found on the ground.
- DU 7, which is the oldest depositional unit encountered, has the biggest trees, reaching 50 cm in diameter, with a high density. Yellow lichens disappear

leaving the boulders covered by moss (25-30%) and white lichens. Organic matter still covers the ground, and in places has grown over boulders.

The establishment of the different DU encountered on site has permitted to evaluate the minimum extent of a series of debris flows occurred in Rebaixader (Fig. 3 and Tab. 1).

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AGE OF DEPOSITIONAL UNITS AND MAGNITUDE FREQUENCY

Table 1 shows the dating results corresponding to the depositional units. The reduced number of wounded trees that has been sampled provided the exact age of only two DU (DU2 and DU3). For the older units (DU4 to DU7) a minimum age was obtained. Minimum ages from colonising trees were also obtained for DU2 and DU3. The comparison of minimum and exact ages for these units suggests that Pinus Sylvestris needs at least 3 years to colonise a new debris-flow deposit.

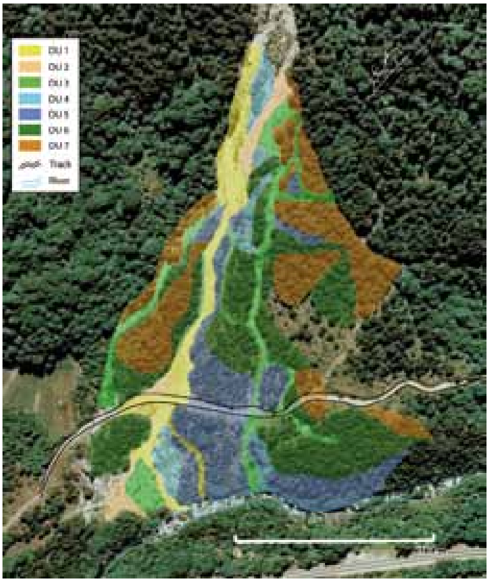

Fig. 3. - Map of debris-flow depositional units at the Rebaixader fan

DU no.	Area (m^2)	Number of sampled trees	Wound age (years)	Age of the oldest colonising tree (years)	DU age	
					Years old	Dendrological year
1	2116	-	-	-	0	active
2	611	162	11	7	11	1997-98
3	2092	147	14	11	14	1994-95
4	1098	62	-	21	21*	1987-88*
5	4157	4	-	25	25*	1983-84*
6	6168	15	-	51	51*	1957-58*
7	4528	17	-	71	71*	1937-38*

Tab. 1 - Area and age of depositional units of Rebaixader fan

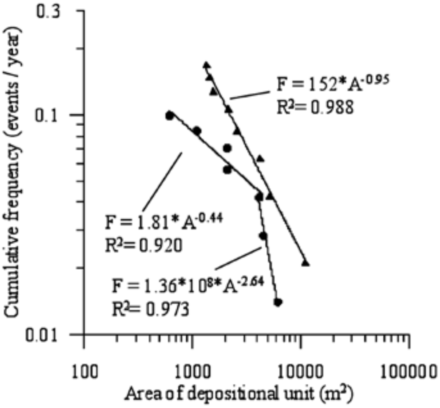

Fig. 4 - Magnitude-Cumulative Frequency curve (logarithmic scaled axes) for the Rebaixader creek. The curve corresponding to another site studied in the Eastern Pyrenees (Tordó Torrent) is also shown (data from C*OROMINAS* & M*OYA*, *2010).*

The tree-ring record at Rebaixader fan spans the last 70 years, during which seven units were deposited. From these numbers, an average return period for debris flows of about 9 years can be obtained. The area of the deposits ranged from 600 to 6200 m^2. However, the frequency of debris flows seems to be higher for the last 25 years (Table 1) with a return period of 5 years.

Figure 4 shows the magnitude-cumulative frequency (MCF) relationship of debris flows at Rebaixader fan. Landslide MCF relationships is usually fitted by a right line (in logarithmic scales) (COROMINAS & MOYA, 2008). The MCF curve fit to the Rebaixader data is, however, strongly nonlinear, or more exactly bilinear. Certainly, the points corresponding to the five smaller depositional units can be fit with a line of a gentler slope than the three bigger ones. Frequency for theses smaller magnitudes is notoriously lower in Rebaixader than in other site studied in the Pyrenees (Tordó torrent). A decrease in the slope of the MCF curve is also commonly reported for other sites and for different types of landslides (COROMINAS & MOYA, 2008). This flattening of the curve, so-called rollover effect, is usually considered as the consequence of an under-recording of small events. In the Rebaixader fan, deposits of some small-magnitude debris flows can have been totally buried by younger events of larger magnitude. In fact, low debris-flow frequency obtained for the period older than the year 1983-84 (Tab. 1) can result from an overlapping of small-magnitude debris flows. It should be noted that the two older depositional units (DU6 and DU7) have also the maximum extent. But such a "double trend"(Fig4) to be confirmed by the study of more debris-flow events.

A shortcoming inherent to tree-ring dating can also explain an under-recording of small debris flows. Accuracy of tree-ring dating is usually of a year, although obviously lower if only minimum ages are obtained. This means that events occurring within a same year cannot be differentiated, and that the assessed depositional units may actually be formed by several debris flows. Relative dating does not permit to distinguish events occurred in a same year, unless cross-cutting relationships were produced.

DISCUSSION AND CONCLUDING REMARKS

It was decided to work out the frequency and the magnitude of past debris flows having left a subsequent trace on Rebaixader's fan. Within the last 70 years, at least 7 debris flows were great enough to create new colonisable surfaces for vegetation. And in the time study, several debris flows of small intensity occurred (Hurlimann *et alii*, 2011).

When compared to another Pyrenean site, it appears that Rebaixader's activity is lesser than expected by the aspect of the fan. However this study suffers limitations and estimates that are likely to bias the analysis:

- The area making up the DU's area is to be understood as the DU's area visible in 2009. No extrapolation has been done, therefore clearly underestimating this parameter.
- The trees ages require the pith to be hit when coring. Because it is not always achieved, we have used a geometric model to add the rings missing between the sample and the pith. This method implies a constant ring width, when nothing proves it is.
- The colonisation time gap (CTG) of Pines in the Pyrenees has not been investigated. 3 years was chosen based on our field data. This value needs further studies.
- DU4 has benefited from several dating techniques used herein. Using branch whorls, a maximum age of 21 years was found, and an average over 60 trees was calculated (13.5 years). Furthermore the biggest tree found on this DU was cored. A minimum age of 13 years was determined. Coring the biggest tree does not mean to date the oldest.
- Debris flows can remain undetected by the approach used here if they occur with a high frequency (greate than on event per year)

This study of debris-flow frequency and magnitude represents a step forward the understanding of Pyrenean debris-flow hazard. Its assessment is actually expressed in terms of susceptibility and frequency-magnitude relationships. Therefore, coupled with the study of the susceptibility of Pyrenean landscapes to debris flows the work presented herein would fulfil the requirements of a debrisflow hazard assessment in the Pyrenees.

Little information is available on the subject, at both catchment and regional scales. More case studies are needed in order to better compare the current dataset and provide accurate analysis and knowledge to communities and stakeholders whose interests are related to debris flows.

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