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Morphology and sedimentology of a complex debris flow in a clay-shale basin

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Abstract

Coupling morphological, sedimentological, and rheological studies to numerical simulations is of primary interest in defining debris-flow hazard on alluvial fans. In particular, numerical runout models must be carefully calibrated by morphological observations. This is particularly true in clay-shale basins where hillslopes can provide a large quantity of poorly sorted solid materials to the torrent, and thus change both the mechanics of the debris flow and its runout distance. In this context, a study has been completed on the Faucon stream (southeastern French Alps), with the objectives of (1) defining morphological and sedimentological characteristics of torrential watersheds located in clay-shales, and (2) evaluating through a case study the scouring potential of debris flows affecting a clay-shale basin. Morphological surveys, grain-size distributions and petrographic analyses of the debris-flow deposits demonstrate the granular character of the flow during the first hectometre, and its muddy character from there to its terminus on the debris fan. These observations and laboratory tests suggest that the contributing areas along the channel have supplied the bulk of the flow material. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: debris flows; clay-shale basin; muddy flow; granular flow; contributing areas

Introduction

In torrential streams, intense storms may trigger sediment transport as hyperconcentrated flows or debris flows. They are a dominant mass movement process in the French Alps and constitute a significant natural hazard. Debris flows usually move downvalley in a series of surges with steep fronts that consist mostly of large boulders. The triggering mechanisms of debris flows are frequently related to an increase in pore pressures due to high-intensity rainfall events (Johnson and Rodine, 1984) or rapid snowmelt (Malet *et al*., 2003a). Channel scour during a debris-flow event can be responsible for great differences in sediment volumes between the triggering area and the deposition area. For instance, Berti *et al*. (1999) noticed that only 10 per cent of the total volume of a debris-flow event in the Dolomites were mobilized from the source area; the rest of the material was incorporated into the flow from the channel. Some debris flows may progressively increase in volume along their flowpath by 10–50 times because of entrainment of loose material and bed scouring (Vandine and Bovis, 2002). However, erosion/deposition processes during the propagation have often been ignored in the debris-flow literature (e.g. Pierson, 1980; Hungr *et al*., 1984; Cenderelli and Kite, 1998; Remaître *et al*., 2002). Only a few studies have tried to quantify the volume of sediment eroded by debris flows during transport and the contribution of this eroded sediment to the overall volume of the event (Benda, 1990; Fannin and Rollerson, 1993). Jakob *et al*. (2000) reported a channel yield rate of 28 m^3/m^{-1} for a debris flow in British Columbia by dividing event volume by runout distance. Runout characteristics of the debris flow (velocity, discharge, thickness) involve the rheological parameters of the surficial deposits incorporated in the flow by erosion processes. In clay-shale basins affected by strong erosion, slopes can provide a large quantity of poorly sorted materials to the torrent (Mathys *et al*., 2003). In such areas, the scoured sediments may change the behaviour of the debris flow in the runout zone.

This paper is illustrated through a careful field survey carried on the Faucon watershed (Barcelonnette basin, Alpes-de-Haute-Provence, France) where on the afternoon of 19 August 1996 a large debris flow occurred. Debris-flow characteristics (triggering conditions, runout characteristics, etc.) gathered by a morphological analysis and a sedimentological investigation are discussed here.

Study Area

Clay-shale basins are usually associated with a variety of rapid slope movements involving different types of material (Malet *et al*., 2003b; Remaître *et al*., 2003). In the Southern French Alps (Figure 1a), several torrential watersheds are prone to debris flows, e.g the Verdarel (Lahousse and Salvador, 2002), or the Boscodon (Bonnet-Staub, 1999). In the Barcelonnette basin (Figure 1c) more than 20 torrents have experienced debris flows since 1850.

The Barcelonnette basin extends from 1100 m a.s.l. to 3000 m a.s.l. (Figure 1c) and is drained by the Ubaye river, which has exposed 1·3 km^2 of autochthonous black marls; the hillslopes are strongly affected by gullying and/or mass movements. The basin is situated in the dry intra-Alpine climate zone with a marked interannual rainfall variability (733 ± 412 mm over the period 1928–2002). Locally, summer rainstorms can be especially intense, yielding more than 50 mm h^{-1} on occasion. On melting, the thick snow cover adds to the effect of heavy spring rain (Flageollet *et al*., 1999). There are approximately 130 days of freezing per year supporting significant daily thermal amplitudes and a

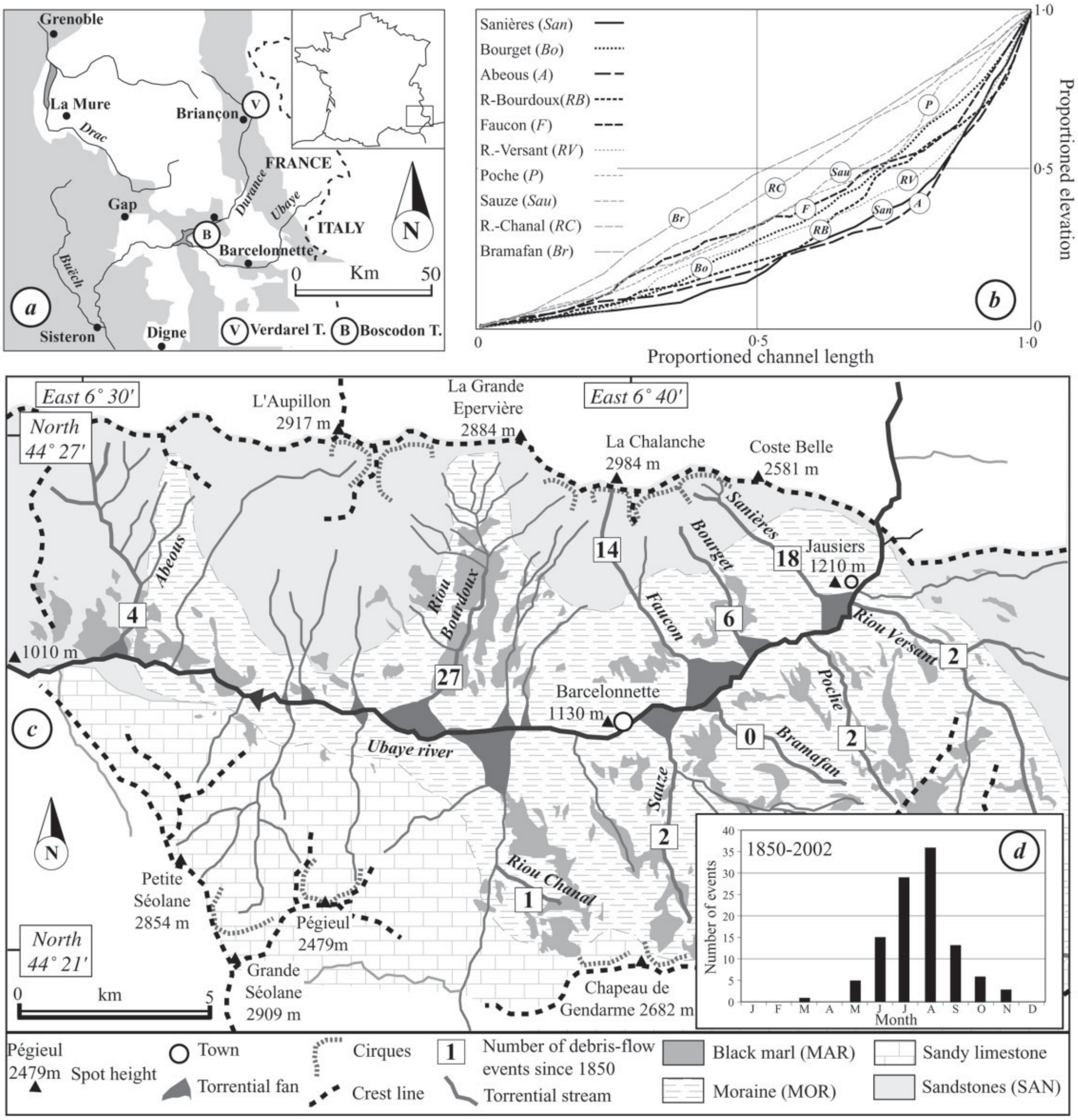

Figure 1. (a) Location map of the Barcelonnette basin and extent (in grey) of the black marl in the South French Alps; (b) proportioned path-profile of ten torrential streams located in the Barcelonnette basin; (c) morphological sketch of the Barcelonnette basin; (d) monthly occurrence of debris-flow events since 1850 in the Barcelonnette basin.

Table I. Morphometric data of ten torrential watersheds in the Barcelonnette basin and estimation of the maximal magnitude (M_l) of a single debris-flow event according to the watershed surface (S)

Stream	Max. elevation (m a.s.l.)	Min. elevation (m a.s.l.)	Channel length (m)	Surface area (km^2)	Channel slope (degree)	Fan slope (degree)	M_l* (10^3 m^3)
Abeous	2811	1020	5400	18·9	0·33	0·15	267
Bourget	2926	1185	4375	6·3	0·40	0·06	113
Bramafan	1981	1160	4175	3·9	0·20	0·09	78
Faucon	2984	1177	5775	10·4	0·31	0·09	168
Poche	2369	1205	3895	5·1	0·30	0·08	96
Riou-Bourdoux	2884	1112	7850	24·6	0·33	0·06	328
Riou-Chanal	2064	1183	2850	2·7	0·31	0·09	59
Riou-Versant	2499	1211	5425	6·2	0·24	0·09	112
Sanières	2872	1214	4550	8·6	0·36	0·08	145
Sauze	2685	1140	5800	4·8	0·27	0·09	92

* $M_l = 27\,000 \times S^{0·78}$ (Rickenman, 1999)

great number of freeze–thaw cycles (Maquaire *et al*., 2003). Various factors, including lithology, tectonics, climate and the evolving landuse, have given rise to the development of torrential streams and several mass movements.

A morphometric study of ten torrential streams (Figure 1c) has been undertaken. The Rickenmann (1999) formula (Table I) gives some values of maximal debris-flow volume ranging between 59 000 and 328 000 m^3. Torrents on the south-facing slope of the Barcelonnette basin are the most affected by debris flows: of the debris flows in the Barcelonnette basin since 1850, more than 120 occurred in the south-facing torrents. This is mainly because: (1) springs are located at the boundary between the permeable, coarser material of the Autapie sheet thrust and the Callovo-Oxfordian black marls (Figure 1c); (2) south-facing slopes are steeper than north-facing, hence the slopes of south-facing torrent streams are higher (0·31 to 0·40) than those facing north (0·20 to 0·33) (Figure1b, Table I). Debris flows occur frequently in summer (90 per cent of recorded debris-flow events between June and September, Figure 1d).

The Faucon watershed (Figure 1c) was selected as an experimental site because an important debris flow occurred in 1996 (Remaître *et al*., 2003) and because the geomorphological and hydrological conditions of the area are quite typical of other torrents evolving in clay-shale outcrops. The Faucon basin (44°25′N, 6°40′E) is a steep forested watershed with an area of approximately 10·5 km^2 which rises to 2984 m a.s.l. (Figure 2). Local slopes are steeper than 25°, reaching 80° at the highest elevations. The higher parts of the massif consist of two sheet thrusts of faulted sandstones and calcareous sandstones. Slopes below this consist of Callovo-Oxfordian black marls, mainly composed of fragile plates and flakes packed in a clayey matrix. Most slopes are covered by various Quaternary deposits: thick taluses of poorly sorted debris; morainic deposits; screes and landslide debris. These deposits have a sandy-silt matrix, may include boulders up to 1–2 m in size and are between 3 and 15 m thick.

The incised channel has an average slope of about 20°, ranging from 80° in the headwater basin to 4° on the alluvial fan, and is approximately 5500 m in length. Channel morphology is characterized by two main types of cross-section: a V-shaped profile with a steep channel, and a flat-floored cross-profile between steep slopes. The Faucon torrent has formed a 2 km^2 debris-fan, that spreads across the Ubaye valley floor (Figure 2). It has a slope gradient ranging from 4 to 9°. The fan consists mostly of cohesionless and highly permeable debris (debris-flows strata and/or torrent deposits).

The Faucon stream has a classic torrential flow regime associating: (1) peak discharges in spring (snowmelt) and in autumn (high precipitation) and, (2) a high variability in summer according to the occurrence of storms. Since 1850, 14 debris flows have occurred in the Faucon torrent. More than 70 check dams were built on the torrent since the 1890s to prevent flooding but only half of them are still efficient (Remaître *et al*., 2002).

Morphological Characteristics of the 19 August 1996 Debris Flow

On 19 August 1996, a debris flow was triggered by an intense and local thunderstorm. Indeed no rainfall was recorded by the pluviograph located at the Faucon alluvial fan (Figure 2). According to eye-witnesses and the French Forest Office, the total duration of the event was about 2·5 hours. The debris flow caused moderate damage and the main road across the alluvial fan was cut for several hours (Figure 3a).

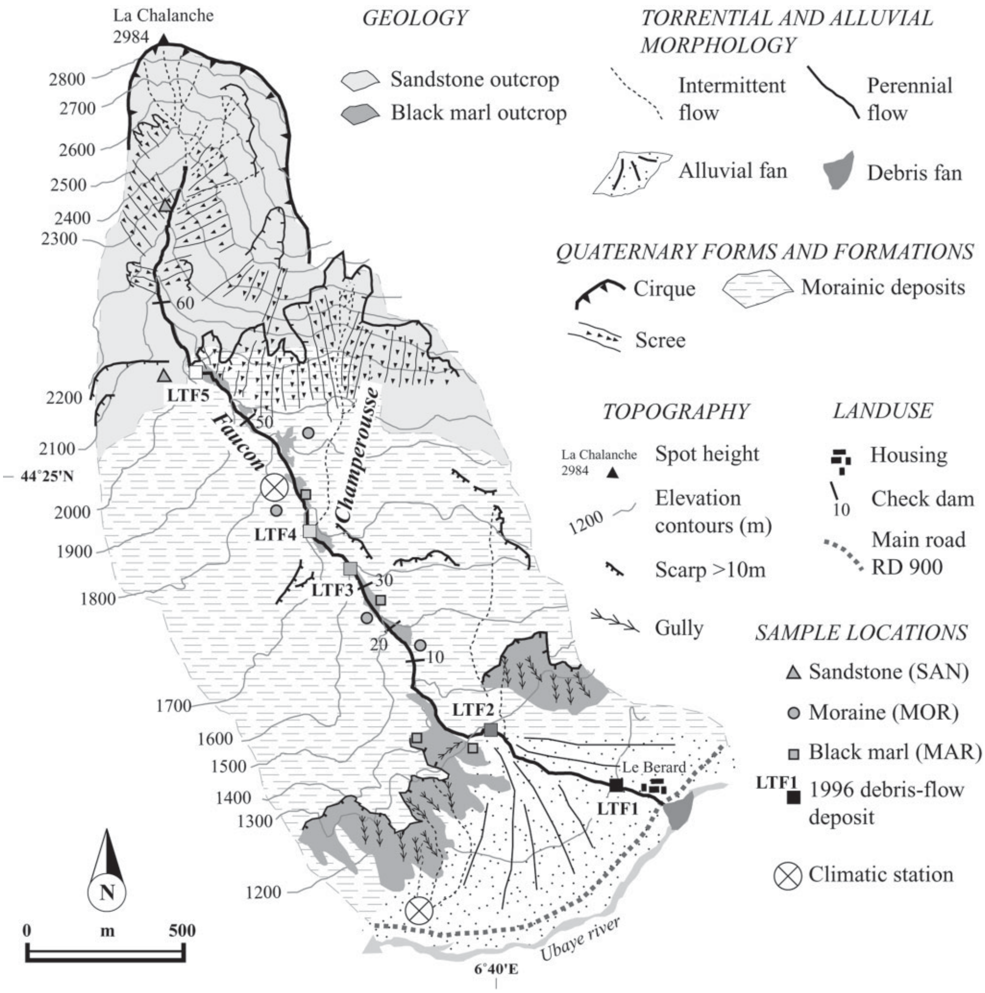

Figure 2. Morphological map of the Faucon watershed.

The source area

The source area of the debris flow in the upper part of the torrent (above 2100 m a.s.l.), consisted of several shallow landslides of moderate size (<100 m^3) on slopes ranging from 30° to 50°. In this section the channel width ranged from 5 to 8 m. The headwater basin has a rocky sandstone substrate, which has been exposed over several square metres by stripping of the surface gravel. This suggests removal of this loose, cohesionless material by sheetflow. The concentration of this loose unconsolidated material behind a natural dam and then the breaking of this dam caused the debris flow. A splatter of fine-grained liquid sediments was found up to 6 m high on trees along both sides of the debris-flow source area which allows an estimate of the height and volume of the breached dam (approximately 5000 m^3 of debris-flow material, e.g. Remaître *et al*., 2002).

The debris-flow path

One thousand metres below the initiation point at the black marl outcrop, the flow path widened by 10 m. The total length of the transport zone is 3000 m with a slope gradient of about 25°. Several areas of erosion were observed (Figure 3c), characterized by shallow weathered black marls and/or Quaternary deposits sliding over the bedrock. During passage of the flow, channel bed scour increased the volume of the debris flow, especially by incorporation of the material from the black marls outcrop (1900 to 1300 m a.s.l.). The scour depth of the surficial cover ranged between 0·5 and 2·0 m. Depending on the channel slope and shape, small lobate deposits (thickness ranging from 0·20

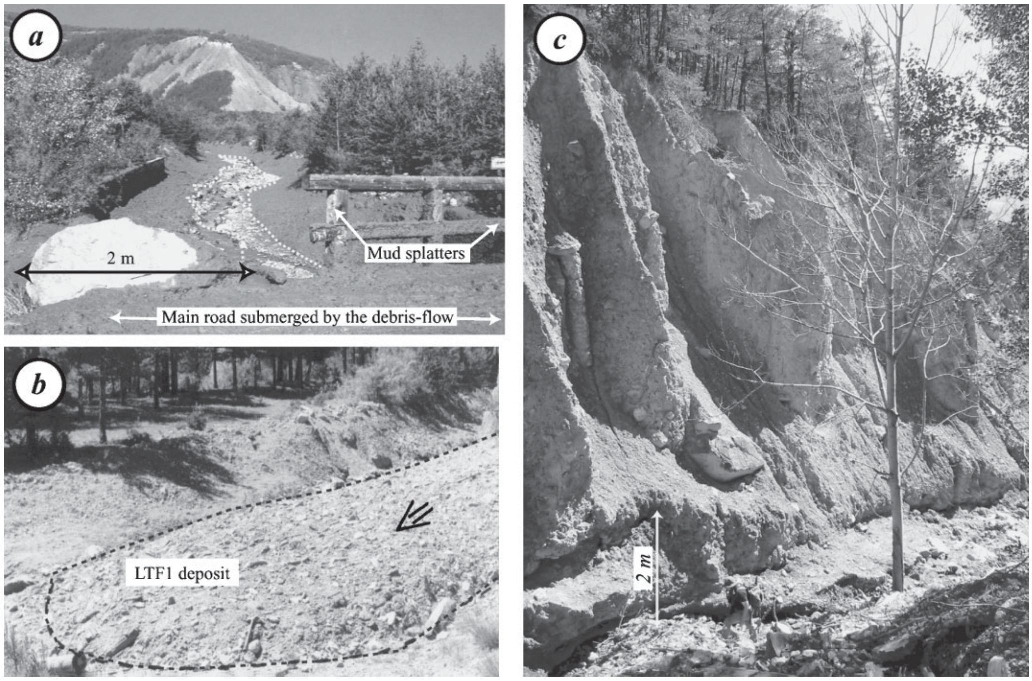

Figure 3. (a) Photograph of the 19 August 1996 debris flow a few hours after the event (photograph taken by N. Masselot published in Sivan, 2000); (b) LTF1 deposit; (c) example of contributing area with high scour depth.

to 1·0 m) of debris-flow pulses could be observed. Lateral and channel-bed deposition occurred downstream between 1300 to 1750 m a.s.l., and formed discontinuous narrow levees rising 2–3 m above the surrounding slopes on both sides of the channel (Figure 4d). The material deposited in the transport zone consisted mostly of clast-rich, slightly bouldery, sandy, muddy gravel, with the clast-rich and coarser fractions of this facies fringing the lobe margins and the top of the levees, where fine boulders and cobbles are concentrated. A strong inverse grading has been observed. Lateral sorting of the debris deposit was poor to very poor, whilst vertical sorting was high. The size of the levees may exceed 100 m in length and 30 m in width. Mapping of the debris-flow deposits in the path allowed us to estimate the volume at approximately 11 000 m^3.

The deposition zone

Only two end-lobes of debris-flow pulses have been found along the channel because authorities cleaned the channel a few hours after the event. The LTF1 deposit (Figure 3b), some 70 m long and 5 m wide, is located a hundred metres below the apex. Most of the debris flow spread over the old (pre-1996) alluvial fan and joined the Ubaye River. The 1996 debris-fan was about 100 m long and 250 m wide, with a thickness ranging from 1·5 to 3·0 m. Its volume was approximately 50 000 m^3. The volume of debris removed from the fan by authorities and that removed by the Ubaye river are unknown.

Volume and Runout Characteristics

Because of the uncertainty arising with regard to the volume of debris-flow deposits and the thunderstorm characteristics, calculation of the flow parameters must be cautiously considered.

Runout characteristics

Runout characteristics were investigated as they are basic to the design of dams, debris retention barriers and bridges. To estimate peak discharge values (Q_{max}), cross-sectional areas of the wetted perimeter were multiplied by the average

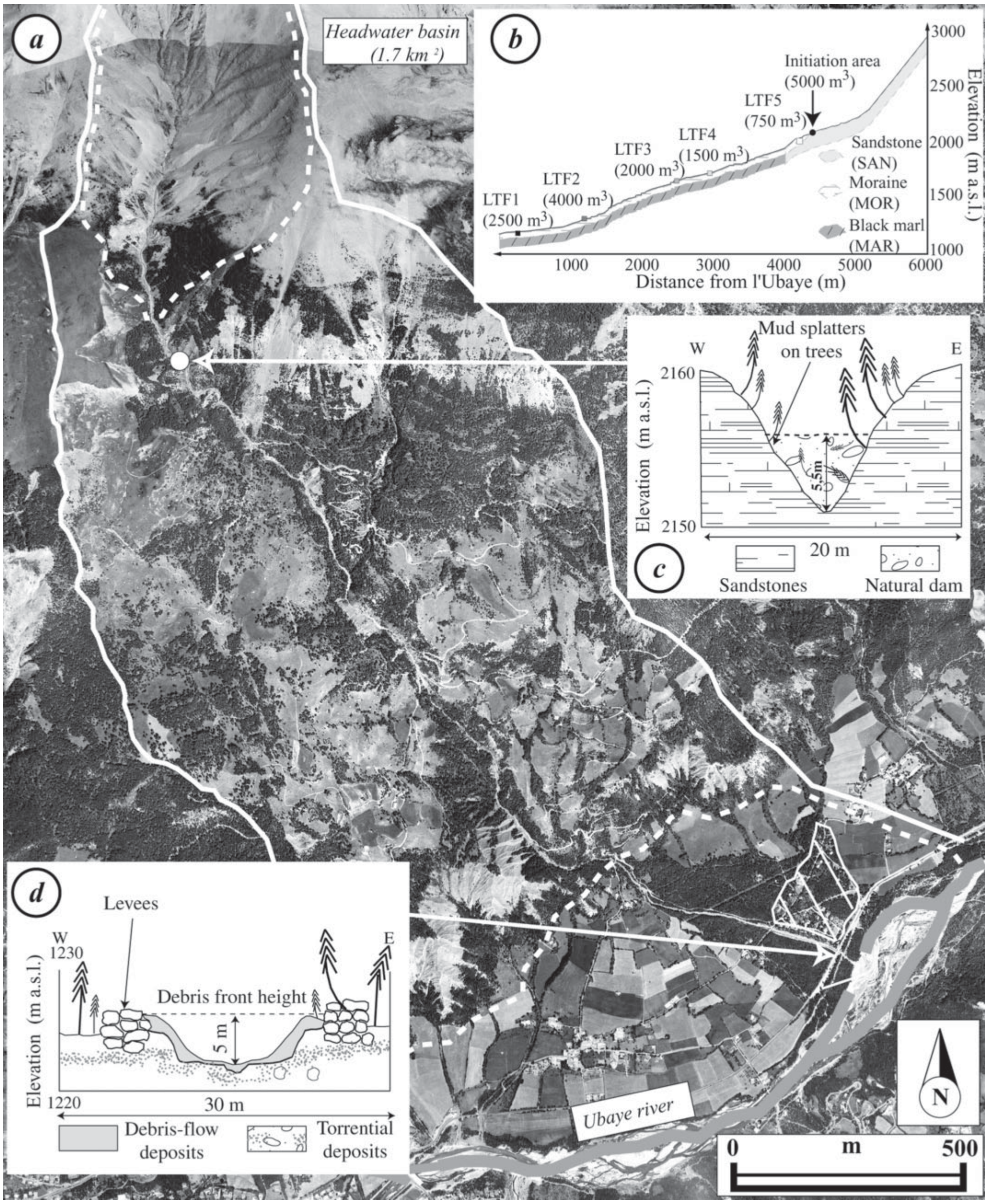

Figure 4. (a) Orthophotograph of the Faucon watershed (August 2000); (b) path profile; (c, d) cross-sections of the Faucon stream.

velocity back-calculated from superelevation in channel bends and the forced vortex equation (Hungr *et al*., 1984). Results are given in Table II.

Volume and scour rate

In torrent hazard assessment, the debris-flow volume is one of the most important parameters (Rickenmann, 1999). As a rough approximation, the maximum total volume of the 1996 debris flow can be back-calculated by comparing results from three methods (Table III): a hydraulic method (total volume), a geomorphological method (sediment volume) and a hydrological method (water volume).

Table II. Velocities and peak discharge (Q_{max}) of the 1996 debris-flow

Station*	Cross-sectional area (m^2)	Channel slope (degree)	Radius of curvature (m)	Banking angle (degree)	Height of runup (m)	Velocity (m s^{-1})		Q_{max} (m^3 s^{-1})	
						Vortex eq.*	Runup†	Vortex eq.	Runup
LTF2	22	11	6·8	21	3·1	5	7·8	110	172
LTF1	21	13	7·5	19	2·8	4·9	6·3	102	132

* Velocity calculated by the forced vortex equation: $v = (gr_c \cos\theta \tan\alpha)^{0.5}$, where g is the gravitational constant, r_c is the radius of curvature of the centreline of a channel bend, θ is the banking angle of the flow, and α is the longitudinal channel slope;
† Velocity calculated by runup ($v = (2gh)^{0.5}$, where h is the height of runup)

Table III. Estimates of debris-flow volume by different methods

Method	Sediment volume (m^3)	Water volume (m^3)	Total solid fraction	Debris-flow volume (m^3)
	200 000	250 000	0·45	
Hydraulic	275 000	175 000	0·60	450 000
	360 000	90 000	0·80	
	15 000		0·45	35 000
Hydrologic	30 000	20 000	0·60	50 000
	80 000		0·80	100 000
		73 000	0·45	133 000
Geomorphologic	60 000	40 000	0·60	100 000
		15 000	0·80	75 000

(1) The ‘hydraulic’ method is based on the total duration of the event (in our case 2·5 h) and the peak maximal discharge. For a triangular hydrograph, the maximal total volume (water and debris) is about 450 000 m^3. Sediment volume can be estimated using the sediment concentration of the flow. Coussot and Meunier (1996) suggest sediment concentrations of 0·45 to 0·80 (volume/volume) which yields a sediment volume of 200 000 m^3 to 360 000 m^3. In this calculation, the sediment concentration is assumed to be constant throughout the duration of the flow event. The total volume is probably overestimated given the inadequacy of a simple triangular hydrograph;
(2) The ‘hydrological’ method requires the estimation of the volume of the rainfall water contributing to the debris flow. With a storm intensity of 80 mm/h (maximal values recorded in the Barcelonnette basin (Malet *et al.*, 2003a), a runoff ratio of 50 per cent and a wetted area of 0·2 km^2 (we suppose that the wetted area is the headwater basin), the total volume of water is about 20 000 m^3. For the same sediment concentration (0·45 to 0·8), the total volume is estimated at 35 000 m^3 to 100 000 m^3.
(3) The ‘geomorphological method’ is based on field surveys of the volume of debris-flow deposits located in the channel and on the debris-fan. Total volume of sediment deposited was estimated to be approximately 60 000 m^3, excluding the volume of sediment transported directly to the Ubaye River. This suggests a range in total volume of debris flow from 75 000 m^3 to 133 000 m^3.

Total volume of sediment deposited in the channel and on the debris fan was estimated to be approximately 100 000 m^3. Channel scour, bank failures and slope contribution are responsible for the difference in sediment accumulation between the 5000 m^3 from the debris source area and the estimated 100 000 m^3 of sediment deposited, which cannot be determined directly because no data were available on the channel fill before this event. For this reasons, channel scour (S) per metre channel was estimated according to the empiric formula proposed by Jakob *et al.* (2000):

$$S = (V_{tot} - V_{ini})/L_c$$

where V_{tot} is the volume of the debris-flow deposits, V_{ini} is the volume of the debris-flow source area and L_c is the channel length from the initiation point to the apex fan. With $V_{tot} = 100\ 000$ m^3, $V_{ini} = 5000$ m^3, and $L_c = 3300$ m, the scour above the fan apex amounts to 29 m^3 per metre channel length. This value is close to the 23 m^3/m^{-1} determined for the Chiliwack River valley (Jakob *et al*., 1997) or the 28 m^3/m^{-1} for the Hummingbird Creek (Jakob *et al*., 2000), both located in British Columbia (Canada). No data on scour rate for European torrents are available for the same geomorphological environment.

Laboratory Tests

In order to investigate the sedimentological and rheological characteristics of the debris flow, five samples (identified as LTF in Figure 5) were analysed. Three surficial deposits, weathered black marls (MAR, Figure 5), morainic deposits (MOR) and sandstones slope deposits (SAN), were considered as the source material, and were also investigated for comparison.

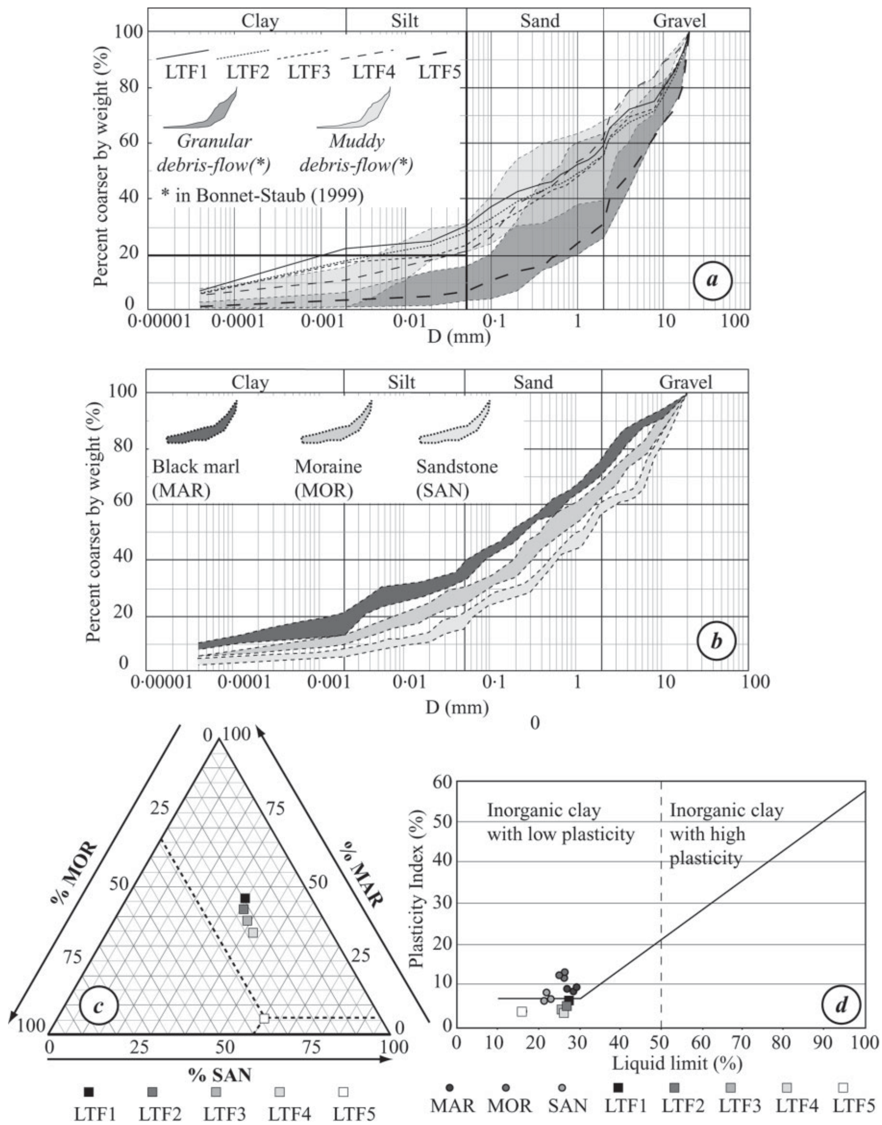

Figure 5. Grain-size distribution of the 19 August 1996 debris-flow (a) and of the three main surficial deposits (b); (c) petrographic analyses of the five debris-flow deposits; (d) Casagrande classification of all the materials.

Particle size of the sediment was established according to the methodology proposed by Maquaire *et al.* (2003). Slope material was sampled from the loose surface cover and at 50 cm depth in the source area. Material from the debris-flow deposits was sampled at 20 and 50 cm depth. The average weight of the samples was about 100 to 150 kg. All samples were oven dried and sieved from less than 20 mm to 0·050 mm. The proportion of fines (<0·050 mm) was analysed by laser diffractometry. Results are summarized in Figure 5a. The particle size distribution obtained on the fraction passing a 20 mm sieve shows a remarkable difference between the five debris-flow deposit samples. The choice of this fraction (<20 mm) for the grain-size distribution characteristics of the material was dictated by practical considerations and has been used by many authors (Bonnet-Staub, 1999; Berti *et al.*, 1999; Hübl and Steinwendtner, 2000); it represents 55–80 per cent of the weight of the total grain-size distribution.

The proportion of fine elements (finer than 0·050 mm) did not exceed 7 per cent for LTF5 (at the head of the torrent), whilst it is more than 30 per cent for LTF1 (on the fan). According to the classification of Bonnet-Staub (1999), LTF5 is a granular debris-flow deposit, LTF1, 2, 3 and 4 are muddy debris-flow deposits (Figure 5a). As can be observed in Figure 5b, it can be assumed that on one hand the bulk of the muddy debris-flow deposits is derived essentially from the weathered black marls and the morainic deposits. On the other hand, sandstone slope deposits bulked the granular flow. Petrographic analyses (Figure 5c) confirm this results.

The particle size distribution confirms that the volume of the initiation zone was very small considering the volume of the final debris-flow deposits. Indeed, the grain-size distribution of the end-lobe (LTF1, more than 20 per cent clay) does not reflect the characteristics of the source material (LTF5, less than 2 per cent clay).

Discussion and Conclusion

A combination of a geomorphological survey and sedimentological analyses provides data on the 1996 debris-flow event. Comparison of the debris-flow deposits with three surficial deposits has helped us to understand triggering conditions and scouring phenomena during this event. Grain-size distribution and petrographic analysis of the debris-flow deposit bring out the granular character of the flow during the first 100 m and its muddy character beyond that point. Geomorphic observations and laboratory tests show the existence of a *sensu stricto* triggering area and several channel scour sources. These contributing areas, characterized by the presence of black marls and a morainic cover, seem to have supplied the bulk of the flow material. This case seems to be specific to debris flow involving soft rocks such as black marl. During the 1996 debris flow, some morphological features have given rise of an increase of the flow volume. But it is still difficult to estimate the part of the additionnal volume for each process, e.g. between bank failures and bed scouring. In order to resolve this topic, a careful geomorphological survey coupled with laboratory tests provides valuable data. Nevertheless, additional work on such clay-shale basins has to be performed in order to determine if such a bulking potential is common or not. Results of this study provide experimental support for numerical modelling of debris-flow runout and spreading. Numerical modelling of debris-flow runout requires a good knowledge of the material behaviour. Grain-size analysis constitutes a first step in the rheological characterization of the material, but some additional tests have to be undertaken. These points are discussed in Remaître *et al.* (in press).

Acknowledgements

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