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Runout modelling and extension of the threatened area associated to muddy debris flows

Modélisation de l'écoulement et extension de la zone exposée à des laves torrentielles boueuses

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Abstract

Debris flows are common in mountainous areas comprising clay-shale outcrops. They can cause severe damage to the environment, life and property. A methodology based on a debris flow runout modelling analysis is presented and discussed. Two watersheds of the Barcelonnette Basin (Southeast French Alps), considered to be prone to debris flows have been investigated and hazard zones on alluvial fans defined. Geomorphological surveys and various geomechanical and rheological tests were undertaken in order to provide data for calibrating a one-dimensional numerical runout model. Calibration of the model against deposit thickness and runout distance allows simulation of several runout scenarios for different properties of the source material and of the flowing sediment-water mixture.

Key words: mass flows, muddy debris flows, rheology, runout modelling, threatened area.

Résumé

Les laves torrentielles sont fréquentes dans les bassins argilo-schisteux en montagne. Elles peuvent causer des dommages considérables aux infrastructures et aux hommes. Une méthodologie fondée sur la modélisation de la propagation de ces écoulements est présentée et discutée. Deux torrents du bassin de Barcelonnette (Alpes-de-Haute-Provence, France), les torrents du Sauze et de Faucon, considérés par le service de la Restauration des Terrains en Montagne comme des bassins "à risque", ont été étudiés. Ces deux torrents ont été récemment le siège d'importantes laves torrentielles. Des données complémentaires issues d'investigations géomorphologique, géotechnique et rhéologique ont été utilisées pour calibrer un modèle numérique d'écoulement unidimensionnel. Le modèle est calé sur les épaisseurs de dépôts et les distances de parcours de plusieurs événements. Des scénarios de propagation en fonction de différentes caractéristiques des matériaux sources et du mélange d'eau et de sédiments sont proposés.

***Mots clés** : écoulements concentrés, laves torrentielles boueuses, rhéologie, modélisation, propagation, zone exposée.*

Version abrégée française

Les marnes noires du Sud-Est de la France sont connues pour leur susceptibilité à l'érosion et aux mouvements de masse (fig. 1). Cet article présente une méthode d'analyse de l'aléa lave torrentielle en calibrant un modèle d'écoulement unidimensionnel, sur deux torrents incisés dans les marnes noires du bassin de Barcelonnette (Alpes-de-Haute-Provence, France), caractérisé par une trentaine de torrents et trois glissements-coulées. Près de deux cents laves torrentielles y ont été dénombrées depuis 1850.

Les travaux menés dans le bassin depuis une dizaine d'années ont montré que ces phénomènes sont déclenchés, soit par la rupture d'un embâcle formé dans un chenal torrentiel, soit par la mobilisation de tout ou partie du volume d'un glissement-coulée. Dans les deux cas, le déclenchement est lié à une saturation soudaine des terrains et une augmentation rapide des pressions interstitielles qui provoque la rupture et la liquéfaction des matériaux.

Deux bassins versants considérés comme des bassins "à risque" par le service de Restauration des Terrains en Montagne, à cause de l'urbanisation du cône torrentiel et des infrastructures routières, et représentatifs de ces deux modes de déclenchement ont été étudiés : le bassin torrentiel du Sauze, où se localise le glissement-coulée de Super-Sauze, où plusieurs laves torrentielles de petits volumes ont

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été observées en 1999 et 2000, et le bassin torrentiel de Faucon où deux laves torrentielles de plusieurs milliers de mètre-cubes se sont produites en 1996 et 2003 (fig. 2, fig. 3).

La modélisation numérique de la propagation s'appuie sur une étude géomorphologique détaillée des deux bassins versants, et sur différentes analyses en laboratoire (caractérisation sédimentologique, géotechnique et rhéologique) et in situ. *L'analyse granulométrique montre que les dépôts des laves torrentielles sont caractérisés par la présence de plus de 20 % de limons et d'argiles, et peuvent donc être définis comme boueux. Pour les laves torrentielles du torrent de Sauze, les courbes granulométriques des zones sources et des dépôts sont très proches. Pour les événements du torrent de Faucon, les analyses ont permis de distinguer deux zones sources distinctes : une zone de déclenchement* stricto sensu *et plusieurs zones de contribution. L'investigation rhéologique montre que les matériaux étudiés se comportent comme un fluide visco-plastique non thixotrope bien représenté par une loi de Herschel-Bulkley. Les paramètres rhéologiques augmentent avec la concentration volumique solide (tab. 1).*

Les simulations numériques ont été réalisées avec le code 1-D BING, qui permet de calculer pour chaque maille d'un profil en long, la hauteur et la vitesse locale d'un écoulement transitoire. Les équations constitutives utilisées pour résoudre l'équation de conservation de la masse et de la quantité de mouvement sont moyennées sur l'épaisseur. Le modèle a été validé sur les événements observés en 1996, 1999 et 2000 sur les deux bassins versants sans procédure de calage spécifique. Les résultats numériques sont en accord avec les observations réelles (fig. 4), notamment pour les épaisseurs de dépôts à l'arrêt (sur le cône), les épaisseurs de dépôts dans le chenal et les distances de parcours. À contrario, les vitesses sont surestimées par le modèle. L'analyse de sensibilité montre que les variations de l'épaisseur des dépôts et la distance de parcours dépendent essentiellement du volume de la zone source et des paramètres rhéologiques (seuil de contrainte, consistance, fig. 5).

Plusieurs scénarios ont été simulés afin de définir les volumes nécessaires à une lave torrentielle pour atteindre les cônes de déjection et provoquer des dégâts. Les scénarios prennent en compte le volume initial de matériau lors du déclenchement, la concentration volumique et les caractéristiques rhéologiques du matériau. Des volumes de 30 000 m^3 et de 15 000 m^3 environ sont nécessaires respectivement dans le torrent du Sauze et dans le torrent de Faucon. Pour ce dernier, la modélisation confirme qu'une lave torrentielle d'un volume initial inférieur à 10 000 m^3 ne peut atteindre le cône de déjection sans apports de matériaux supplémentaires. Les caractéristiques rhéologiques de la zone source et des zones de contribution ont une influence de premier ordre sur les distances de parcours et les épaisseurs de dépôts (fig. 6).

Afin d'obtenir une estimation plus fine des volumes nécessaires, des efforts supplémentaires doivent être réalisés dans le développement de codes numériques qui tiennent compte des zones contributives (matériaux du chenal et des berges incorporés à l'écoulement pendant la propagation), et dans la représentation de l'étalement des matériaux sur le cône pour le zonage de l'aléa.

Introduction

Muddy debris flows are concentrated slurries of water, fine solids, rocks, boulders and debris. Typical velocities of such landslides range from metres per second to ten metres per second. Typical volumes of sediment range from a few thousand to a few million cubic metres. Finally typical runout distances are from hectometres to kilometres (Ancey, 2001). The hazard posed by debris flows is common to all mountain environments and such landslides are a major source of property damage. Two major human activities affected by such phenomenon are transport and construction. Typical recent examples in Europe include the debris flow that occurred in the Pissot torrent (Switzerland) in August 1995, which hit the motorway linking Lausanne to Montreux (property damage estimated at 20 millions Euros, Meylan, 1996), and the debris flow that occurred on the Italian section of the Trento-Bolzano-Brennero motorway in August 1998 (5 people killed, D'Agostino and Marchi, 2001). Moreover, debris flows can spread out on alluvial fans and destroy buildings, sometimes killing or injuring the inhabitants. Typical examples in Europe include a catastrophic series of debris avalanches and debris flows in Sarno in Italy (160 people killed in May 1998). Further, the hazard posed by debris flows is relevant not just to the local inhabitants but to all users of these environments. For example, the Biescas campsite tragedy in the Spanish Pyrenees (August 1996) affected holidaymakers from all Europe (Alcoverro *et al.*, 1999).

For muddy debris flows, many scientific gaps still remain: (1) triggering mechanims and estimation of the volumes of material that can be mobilized, (2) flow dynamics, (3) extension of the threatened area for various rheologies and stoppage conditions, (4) estimation of the intensity and temporal occurrence. The methodology to assess the hazard posed by these complex phenomena has to be improved by a multi-disciplinary approach and the joint use of historical, morphological, geotechnical and geophysical investigations, supported by numerical simulations (Rickenmann and Koch, 1997; Crosta, 2001; Bardou, 2002). Models, considered by the risk manager as a tool for the process of decision-making, have to be calibrated on well-documented events and field observations.

The purpose of this paper is to present a methodology for assessing the hazard posed by debris flows. We calibrate a mathematical runout model on two torrents incised in the black marls of the Barcelonnette Basin (Alpes-de-Haute-Provence, France). In black marls, rapid mass-movements like debris flows or debris avalanches initiate from either the simultaneous contribution of several material sources (by slow and continuous erosive processes on slopes), or a single source (by the fluidization of a slow-moving landslide). If triggered from a single source, the volume of materials can be very large depending on the total volume made available at the source.

Two watersheds, considered as "basins at risk" by the French Forest Office and characteristic of the two types of initiation have been studied: the Sauze torrential catchment, where two small-volume muddy debris flows originated from the Super-Sauze earthflow in 1999 and 2000 (Malet *et al.*, 2003a), and the Faucon catchment impacted by a large debris flow in 1996 (Remaître *et al.*, 2003a). Main objectives of the study are to: compare the physical characteristics (grain-size distribution, behaviour) of these flows and the related source material; calibrate a runout model against well-documented events representative of debris flows involving clay-shale; model the debris flow runout assuming several scenarios in order to: (1) identify the minimum volume necessary to reach the alluvial fan, and (2) evaluate the influence of various characteristics of the source material on the behaviour of the flow and on the extent of the runout.

Triggering mechanisms, morphology and behaviour of rapid mass movements in clay-shale terrain

In torrential streams, intense and localised storms may trigger muddy debris flows. They usually move downvalley in a series of surges with steep fronts that consist mostly of large boulders. During the last decades, considerable research has focused on debris flow triggering mechanisms (Johnson and Rodine, 1984) and behaviour of the bulk material (Johnson, 1965 ; Takahashi, 1991; Coussot, 1997; Iverson, 2003). All these physical theories to describe triggering, flow and deposition processes of debris flows were based on the treatment of the bulk material as one or two phases.

In France, debris avalanches and debris flows are frequent on the slopes and in the channels of torrential basins composed of black marls. According to eyewitness observations, and on the basis of Hungr's classification (Hungr *et al.*, 2001), five types of rapid mass movements occur in black marls: slow-moving earthflows, moderately moving mudflows, muddy debris avalanches, muddy debris flows and hyperconcentrated flows (Malet *et al.*, 2003b). As shown by figure 1A, a continuous spectrum of flow phenomena is observed in the black marl terrain between Grenoble and Nice (fig. 1B), from sediment-laden rivers, through ephemeral streams to the various types of rapid mass movements. Figure 1A also indicates that the transition from mass transport to mass movement takes place at a saturated unit weight, γ_{sat}, of about 18.6 to 19.6 kN.m^{-3}. Freshly mixed concrete, with a γ_{sat} of about 22.6 kN.m^{-3}, provides a close analogue, in this and other respects, for dense debris flows as suggested by J.N. hutchinson (1988). The spectrum of processes is discussed, from a rheological point of view, by T.C. Pierson and J.E. Costa (1987), P. Coussot and M. Meunier (1996), and R.M. Iverson (1997). Another important parameter of rapid mass movements is their grain-size distribution (fig. 1C). The slow-moving earthflows are widely graded, with a clay fraction of more than 25%. A strong contrast appears with the fast-moving muddy debris avalanches and muddy debris flows, which show a clay fraction of about less than 20%.

In summer, muddy debris flows can be initiated by two major types of mechanisms. Initiation can occur in a torrential stream during an intense and localised thunderstorm through concentration of runoff and loose material supplied by shallow landslides (Berti *et al.*, 1999); breaking of a natural dam (Capart *et al.*, 2001); bed fluidization or channel-bed failure (Tognacca and Bezzola, 1997); and damming of the stream by a landslide (Iverson *et al.*, 1997). In all cases, the triggering mechanisms are frequently related to an increase in pore pressure due to high-intensity rainfall events or rapid snowmelt with subsequent saturation and failure of slope materials. Debris flows may progressively increase in volume along their flowpath by 10-50 times because of the bulking effect (entrainment of loose material and bed scouring) (e.g. Pierson, 1985; Vandine and Bovis, 2002).

Initiation can also occur through the liquefaction of slow-moving landslides. In a limited number of cases, landslides can accelerate suddenly in relation to progressive saturation and sudden development of pore water pressure, fail in a plastic fashion, and fluidize. In recent years many landslides have occurred in Europe, following long rainy events or periods of rapid melting and thawing of frozen soil. Typical examples include La Valette in France (Colas and Locat, 1993), Vallcebre in Spain (Corominas and Moreno, 1988), Alverà in the Italian Dolomites (Gasparetto *et al.*, 1996), or some earthflows in the Basento valley (Southern Italy; Pellegrino *et al.*, 2000). In the black marl of the French Alps, termed "Terres Noires", three large earthflows (Poche, Super-Sauze and La Valette) have initiated more or less mobile debris avalanches and debris flows in recent years (Le Mignon and Cojean, 2002; Maquaire *et al.*, 2003), with volumes ranging from 5,000 m^3 to more than 60,000 m^3 at La Valette in 1988 (e.g. van Beek and Van Asch, 1996).

The Faucon and the Sauze catchments and their debris flow events

The Faucon and the Sauze catchments are located, respectively, on the south-facing slope and on the north-facing slope of the Barcelonnette Basin (Alpes-de-Haute-Provence, France, fig. 2A). The Ubaye River drains the Barcelonnette Basin, which slopes up from 1100 to 3000 m a.s.l. The upper rock crest comprises two massive thrust sheets (Parpaillon and Autapie). The Ubaye River has carved out 13 000 ha in the autochthonous black marl. Marly hillslopes are strongly affected by gullying and landslides. The major part of the rocky substratum is covered by Quaternary deposits, mostly consisting of moraines, screes, and landslide accumulations. A number of factors, including lithology, tectonics, climate, and evolving land use, have given rise to the development of 26 torrential streams and various slope movements. There have been some 150 debris flows in the Barcelonnette basin since 1850 (Flageollet *et al.*, 1999).

The Faucon torrential stream, which drains a 10.5 km^2 basin to the south, joins the Ubaye upstream of the developed area on a fan at 1170 m a.s.l. (fig. 2A, 3A). Local slopes

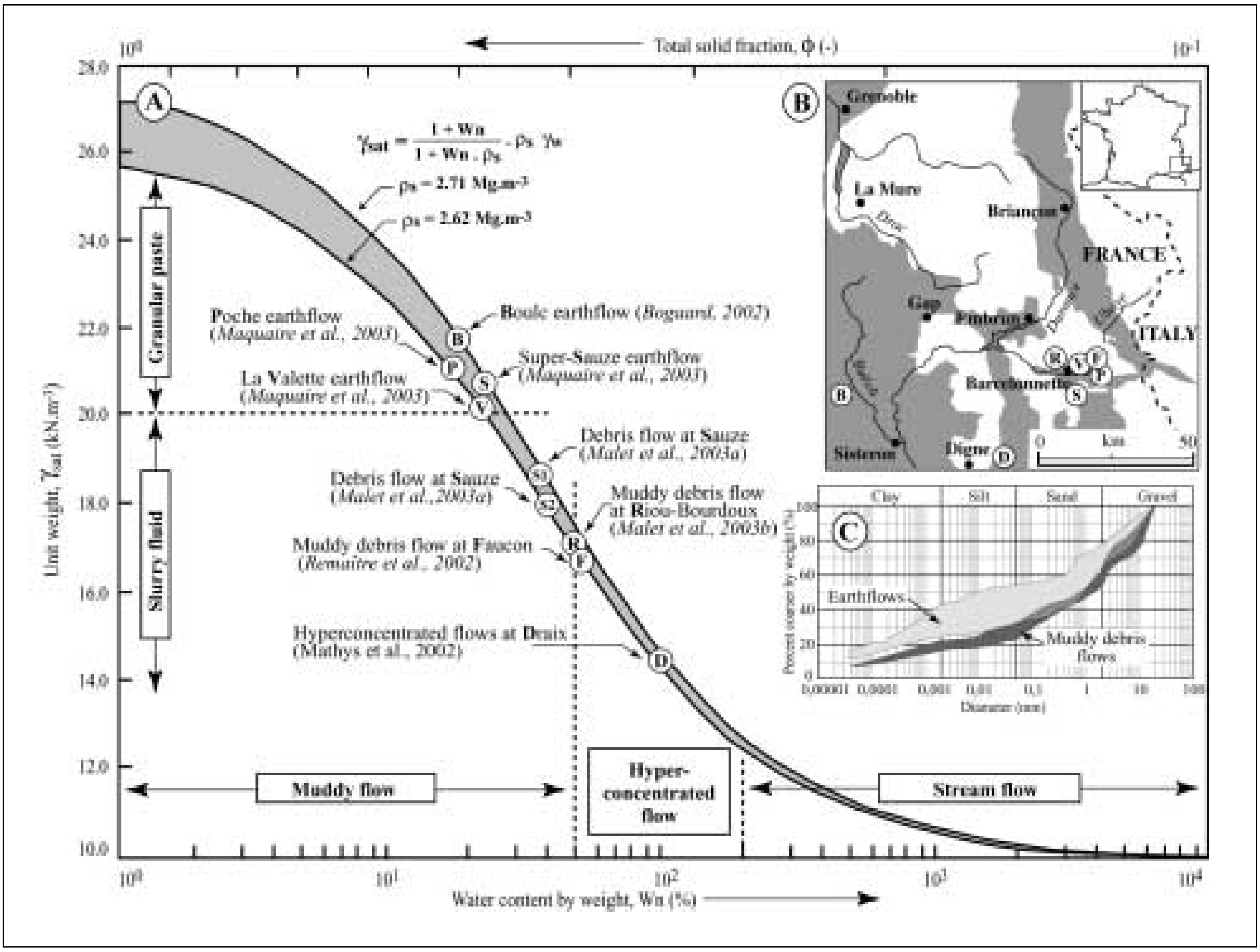


Fig. 1 – **Typology of flow-like landslides occurring in black marls of Southeast France**. A: continuous spectrum of sediment concentration, from sediment-laden rivers to muddy debris flows (modified from Hutchinson, 1988); B: black marls terrain in South East France and location of the main flow-like landslides; C: typical grain-size distribution of the black marl flow-like landslides.

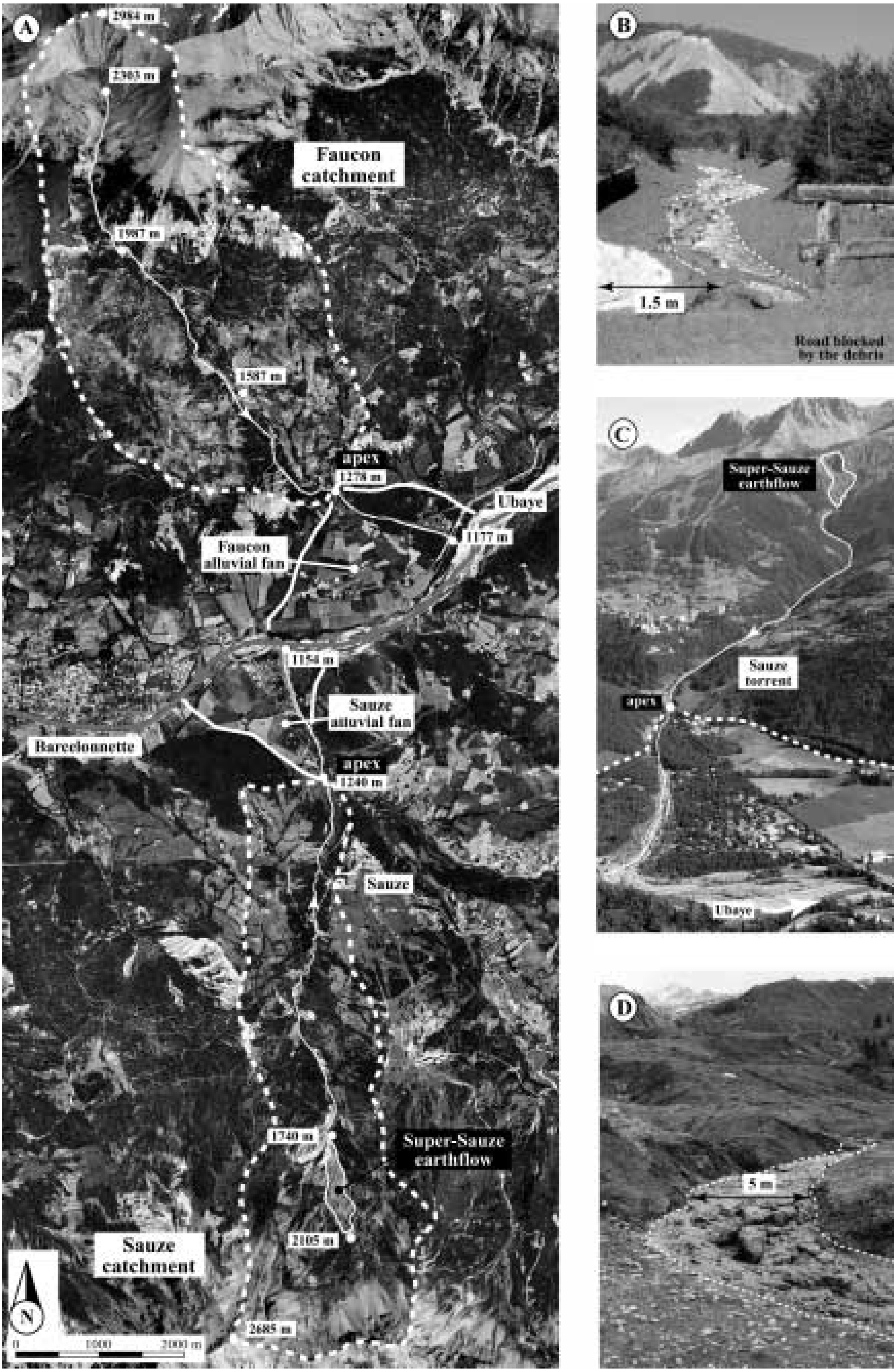
*Fig. 1 – **Typologie des écoulements gravitaires rapides dans les marnes noires du Sud-Est de la France**. A : classification des écoulements concentrés en fonction de la concentration volumique solide, des sédiments alluviaux aux laves torrentielles (modifié d'après Hutchinson, 1988) ; B : extension des marnes noires dans le Sud-Est de la France et localisation des principaux écoulements gravitaires rapides ; C : courbe granulométrique typique d'un dépôt d'un écoulement gravitaire évoluant dans les marnes noires.*

are steeper than 25°, reaching 80° on the highest stretches in the headwater basin. Bedrock geology of the upper part of the basin is characterized by the two thrust sheets made up of limestones, sandstones and flyschs. Black marls dominate the basin. Apart from the channel and its side slope, the basin is covered by Quaternary deposits (moraine and scree), varying in thickness between 3 and 15 m. Quaternary deposits are susceptible to landsliding because they are steep and they become saturated during extended periods of high precipitation. The Faucon torrent has formed a huge debris-fan (fig. 2) that spreads across the Ubaye valley floor. The torrential fan extends southward for about 1 km and covers an area of 2 km^2; its slope ranges from 6 to 9°. Since 1850, 15 debris flows have occurred in the Faucon stream. The average frequency of debris flow occurrence is about one event every 10 years (Remaître *et al.*, 2002).

On August 19, 1996, a debris flow was triggered in the Faucon stream by an intense and localised thunderstorm and by the breaking of a natural dam (2100 m a.s.l.) by loose material concentrated in the stream channel (fig. 2B). The estimated volume of the material mobilised in the source area was approximately 5000 m^3. Downstream, the flow severely scoured the channel bed, increasing the volume of

Fig. 2 – **The Faucon and the Sauze torrential catchments and their debris flows events**. A: orthophotographs of the Faucon and Sauze catchments (July 2000); B: the 1996 Faucon debris flow overflowing at the fan apex; C: general view of the Sauze catchment illustrating the concept of a "basin at risk"; D: the 1999 DF2 debris avalanche in the main central gully of the Super-Sauze earthflow.

*Fig. 2 – **Les bassins torrentiels de Sauze et du Faucon et leurs événements associés**. A : photographie orthorectifiée des bassins du Sauze et de Faucon (Juillet 2000) ; B : la lave torrentielle du torrent de Faucon en 1996 au niveau de l'apex ; C : vue générale du bassin torrentiel du Sauze illustrant le concept de bassin de "risque" ; D : la coulée de débris observée dans la ravine centrale du glissement-coulée de Super-Sauze.*


A
2964 m
2303 m
Faucon catchment
1987 m
1587 m
apex
1278 m
Ubaye
1177 m
Faucon alluvial fan
1154 m
Sauze alluvial fan
Barcelonnette
apex
1240 m
Sauze
1740 m
Super-Sauze earthflow
2105 m
Sauze catchment
N
0
1000
2000 m
2685 m
B
1.5 m
Road blocked by the debris
C
Super-Sauze earthflow
Sauze torrent
apex
Ubaye
D
5 m

the debris flow. Entrainment of material was particularly severe in the black marls (1900 to 1300 m a.s.l.). Lateral and channel bed deposition occurred downstream from 1500 to 1200 m a.s.l. The deposits form discontinuous narrow levees rising 2-3 m above the surrounding slope on both sides of the channel (fig. 1C). Length and width of the levees can reach more than 100 m and 30 m, respectively. Lobate debris deposits were about 150 m wide and 200 m long with an average thickness of 1.5 m on a slope ranging from 8 to 12°. Surface material displays various sizes and shapes. Lateral sorting of the debris flow deposit is poor, whilst vertical rough sorting is high. The coarser clasts and the boulders are concentrated at the top of the flow surface, producing inverse grading, as observed by J.J. Major (1998). The total volume of the debris deposit was estimated to be approximately 100,000 m^3. Channel scour is responsible for the difference in sediment accumulation between the 5000 m^3 of the breached dam and the 100,000 m^3 of sediment deposited. Channel scour, estimated with the empiric formula of M. Jakob *et al.* (2000), amounts to 29 m^3 per meter channel length. The velocities (approximately 5 $m.s^{-1}$) were calculated using the forced vortex equation (Johnson and Rodine, 1984) and multiplied by the cross-sectional area to obtain peak discharge estimates that ranged from 90 $m^3.s^{-1}$ to 110 $m^3.s^{-1}$.

The Sauze torrent extends over a surface of 4.8 km^2, between 2685 m and 1140 m in altitude, for a length of 5.8 km. The flow regime of the torrent is characterized by high discharges (due to snowmelt) in May and June and by summer floods generated by cloudbursts. Floods may also occur in autumn, but the catchment elevation is such that late-year precipitation generally occurs as snowfall. The Sauze drainage basin is characterized by an upper rock basin consisting of limestone formations partially covered by moraine tongues, whereas the median and downstream parts are cut into black marl. The alluvial fan at the base of the torrent is highly urbanized (fig. 2A, 2C) and thus very vulnerable to debris flow hazard.

The headwater basin is characterized by the presence of an active earthflow located between 2105 m (crown) and 1740 m (toe of the flow) for an average slope that reaches 25° (fig. 2A, 2B, 3B). Uphill, the main scarp cuts into moraine deposits and underlying *in situ* black marl. Geotechnical investigations and geophysical prospecting indicate that the earthflow fossilizes an intact topography formed by a succession of crests and gullies. The flow is structured in two vertical units. The first unit, 5 to 10 m thick, is an active and wet viscous formation, while the second, with a maximum thickness of 10 m, is a stiff compact, impervious and stable formation. Two materials derived from the black marls can be distinguished in the upper part of the earthflow, according to their textural characteristics (IND, C1a, fig. 3B). The total volume is estimated at 750,000 m^3 and velocities (recorded *in situ* by an extensometer device and GPS measurements) lie in the range of 0.01 to 0.40 $m.day^{-1}$. Groundwater levels ranging between -2.0 to -0.4 m characterize the earthflow. Sudden rises of the groundwater table cause accelerations of the flow (Malet *et al.*, 2002a). The upper unit can trigger rapid flow-like phenomena, such as in May 1999 when two muddy debris flows and a dozen small mudflows occurred.

On May 5th 1999, (12:10 am GMT), a volume of material (DF1) failed suddenly from the upper part of the earthflow, flowed rapidly down the hillslope and reached the torrent (fig. 3B). The peak velocity varied from upstream to downstream at 3.8 $m.s^{-1}$, 4.9 $m.s^{-1}$, 5.1 $m.s^{-1}$, 4.7 $m.s^{-1}$ and 4.1 $m.s^{-1}$. During the night of May 12-13, 1999 a second larger volume of material (DF2) failed in the same area. The material flowed along the same path as the earlier event. In both cases, deposits were mainly levees or small accumulation lobes and the material continued to flow for five days. Velocity and water content (samples were taken at several locations over a depth of 0.80 m) were surveyed for both events. The water contents were quite homogeneous over depth. The decrease in velocity was correlated to the decrease in average water content. On the first day, the average water content corresponded to the liquid boundary threshold ($W_L = 33\%$). After three days the average water content had decreased only by 9%, and remained higher than the average moisture content observed at Super-Sauze (Malet and Maquaire, 2003). Detailed mapping of the deposits and comparison of two topographic Digital Elevation Models permits an estimate of the volumes at 2,500 m^3 for the first event, and at 7,700 m^3 for the second event (fig. 3B). It is important to note that at the beginning of year 2004, only small volumes were released (from 5,000 to 10,000 m^3) from the Super-Sauze earthflow (750,000 m^3). However geomorphological evidence and eyewitness observations suggest that the release of larger volumes is a realistic hypothesis, under specific climatic and hydrological circumstances.

Methodology and presentation of the BING code

A three-step analysis was followed to assess the extension of the area threatened by muddy debris flows: (1) the geomechanical and rheological properties of the material were characterized, (2) the debris flow propagation code BING was validated on the observed events, and (3) the runout scenarios for different failures having different properties were estimated. The geomechanical properties (grain-size distribution, consistency limits, undrained shear strength) and the rheological properties (yield stress, τ_c and consistency, κ) of the source material were determined by coupling geomechanical tests, rheometrical tests and inclined-plane tests (Malet *et al.*, 2003b).

The one-dimensional flow-dynamics model BING, developed by J. Imran *et al.* (2001) for the study of the downslope spreading of finite-source debris flow, has been used. This code has been validated either for the study of submarine fast slope movements (Marr *et al.*, 2002; Locat *et al.*, 2004) or for subaerial debris flows (Remaître *et al.*, 2003b; Malet *et al.*, 2004). The model incorporates various rheological models (Bingham, Herschel-Bulkley, bilinear; fig. 4A) of viscoplastic fluid. For these simulations, the most widely

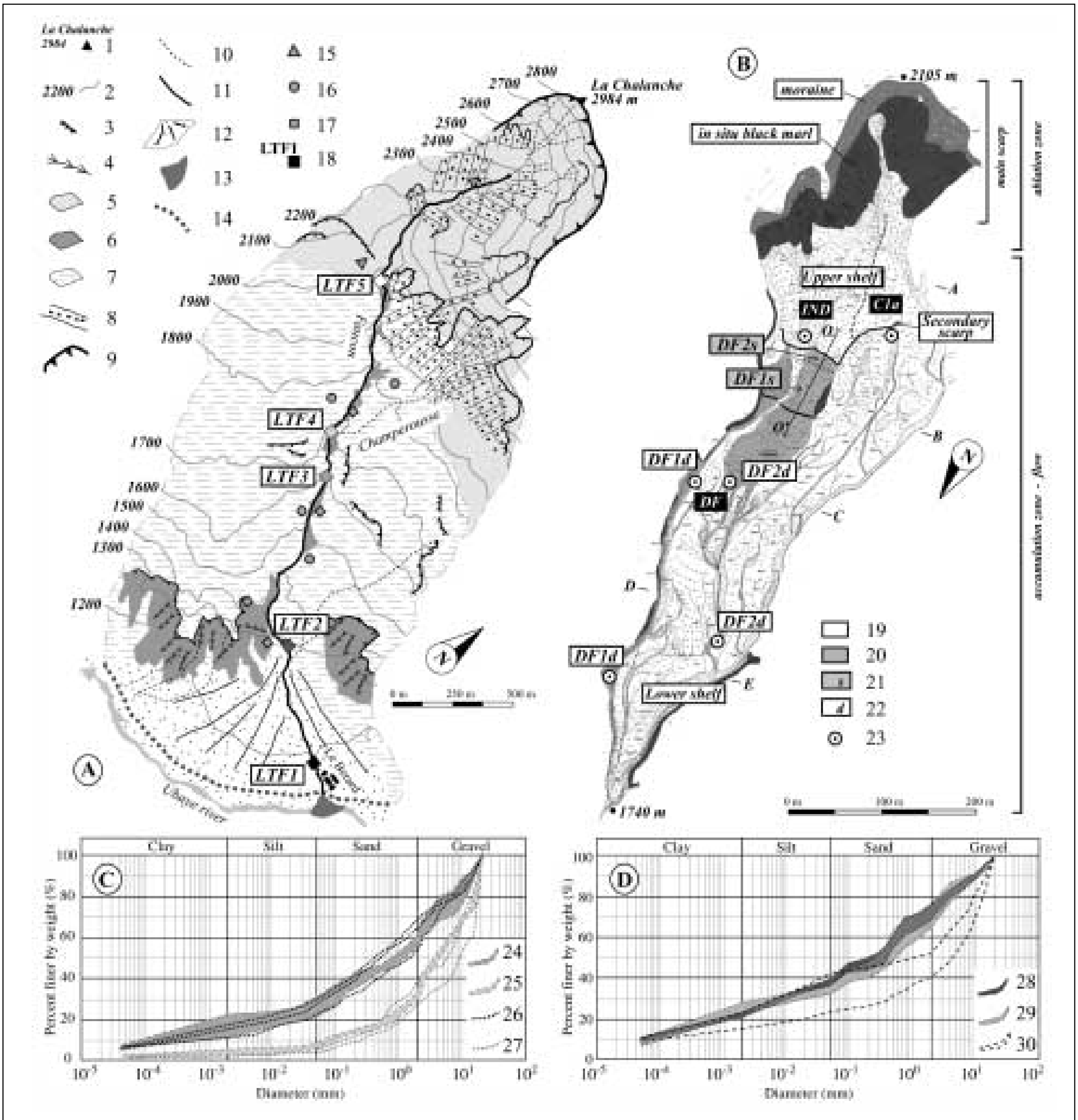


Fig 3 – **Morphological sketch of the Faucon catchment (A) and the Super-Sauze earthflow (B) and associated grain size distribution of the surficial formations (C, D)**. 1: spot elevation (m a.s.l.); 2: elevation contours; 3: scarp > 10m; 4: gully; 5: sandstone outcrops; 6: black marl outcrops; 7: morainic deposits; 8: scree; 9: cirque; 10: intermittent flow; 11: perennial flow; 12: alluvial fan; 13: debris fan; 14: main road (RD900); 15: sample location of sandstone (SAN); 16: sample location of moraine (MOR); 17: sample location of black marls (MAR); 18: sample location of debris flow deposits; 19: reworked black marls; 20: deposits of the 5th May (DF1) and 13th May 1999 (DF2) debris flows at Super-Sauze; 21: source area of the flow event; 22: deposition area of the flow event; 23: sample location; 24: LTF1-LTF4 deposits; 25: LTF5 deposit; 26: black marls (MAR); 27: sandstones (SAN); 28: DF1/DF2 deposits; 29: IND formation, 30: C1a formation.

Fig 3 – ***Morphologie du bassin torrentiel du Faucon (A) et du glissement-coulée de Super-Sauze (B) et granulométrie des formations superficielles associées (C, D)****. 1 : point coté ; 2 : courbes de niveau ; 3 : escarpement > 10 m ; 4 : ravine ; 5 : flyschs ; 6 : marnes Noires ; 7 : dépôts morainiques ; 8 : tablier d'éboulis ; 9 : cirque ; 10 : écoulement intermittent ; 11 : écoulement pérenne ; 12 : cône de déjection ; 13 : cône de la lave torrentielle de 1996 à Faucon ; 14 : route départementale (RD900) ; 15 : localisation des prélèvements de flyschs (SAN) ; 16 : localisation des prélèvements de moraine (MOR) ; 17 : localisation des prélèvements de marnes noires (MAR) ; 18 : localisation des prélèvements de dépôts de laves torrentielles ; 19 : marnes noires remaniées ; 20 : dépôts des laves torrentielles du 5 mai (DF1) et du 13 mai 1999 (DF2) à Super-Sauze ; 21 : zone source des écoulements ; 22 : zone de dépôt des écoulements ; 23 : localisation des prélèvements ; 24 : dépôts LTF1-LTF4 ; 25 : dépôt LTF5 ; 26 : marnes noires (MAR) ; 27 : flyschs (SAN) ; 28 : dépôts DF1/DF2 ; 29 : formation IND, 30 : formation C1a.*

used Herschel-Bulkey rheology (Coussot, 1997) was considered because it results in more accurate models of rheological behaviour when adequate experimental data are available (fig. 4B, 4C). Both choices (rheological model and flow dynamics model) were mainly guided by the fact that all debris flows observed in clay-shale basins comprise a significantly clay and silts fractions. This will be clearly exposed in the section describing the rheological tests.

In the Herschel-Bulkley rheology, the mud is considered to consist of a distinct shear layer and a plug layer. The shear stress at the interface of these two layers is the yield stress. The material can undergo deformation only if the applied stress exceeds the yield stress.

The layer-integrated conservation equation of mass and momentum balanced are solved in a Lagrangian framework using an explicit finite difference scheme developed by L. Jiang and P. Le Blond (1993). A Lagrangian framework has been chosen in order to reduce the duration of the calculation and the flow is assumed to remain laminar throughout the computation. The solution procedure is similar to the ones described by S.V. Savage and K. Hutter (1991) and L. Pratson *et al.* (2001). Let x denote an arc length streamwise coordinate imbedded into the boundary over which the debris flow is to run, y denote the direction upward normal to the bed, and u and v denote the corresponding flow velocities. Then the equations of mass and momentum conservation take the following forms (e.g. Imran *et al.*, 2001):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

and

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\left(1-\frac{\rho_a}{\rho_d}\right)g\frac{\partial D}{\partial x}+\left(1-\frac{\rho_a}{\rho_d}\right)gS+\frac{1}{\rho_d}\frac{\partial \tau}{\partial_y} \qquad (2)$$

where D is the flow thickness, ρ_d and ρ_a is the density of the debris slurry and the ambient fluid respectively, S denotes the slope, g is the acceleration due to gravity and τ is the shorthand for the component τ_{xy} of the stress tensor.

Starting from an initial parabolic shape, the debris mass is allowed to collapse and propagate until the front velocity decelerates to a negligible value at which point the calculation is terminated. The model enforces a no-slip bed condition. Erosion, deposition, and entrainment of water and sediment during the runout are neglected (Marr *et al.*, 2002, Imran *et al.*, 2001). The number of grid cells remains the same throughout the calculation. Each grid node is allowed to move at the local depth-averaged velocity after each time step. As a result neighbouring nodes can move closer or away from each other.

The model needs several input parameters: the longitudinal profile, the failed volume and geometry and the sediment properties. Values of the input parameters are determined from previous work on the study area (Malet *et al.*, 2003b, Remaître *et al.*, 2003a). The reader is referred to these papers for a detailed explanation of the morphological and sedimentological characteristics. The longitudinal path profile is obtained from careful morphological mapping by GPS. As the BING code approximates the failure geometry by two parameters (length, L; thickness, H), the sediment volumes are estimated as follows: the lobe volumes (m^3) are converted to volume per unit width, v, (m^2) by dividing the volume of the source area by the failure area width. As a consequence of working in one dimension, the initial value of L and H must be larger than what is realistic to run the simulation with a correct volume. The relationship as a function of L and H defined by J.G. Marr *et al.* (2002) was used to obtain the correct volume.

Mechanical characteristics and behaviour of the debris flow material and the source material

In order to investigate the geomechanical and the rheological characteristics of the debris flow deposits, several samples of five deposits of the 1996 Faucon debris flow (LTF1 to LTF5) (fig. 3A) and several samples of four deposits of the Sauze event (DF1, DF2, fig. 3B) were analysed. The source materials, that is the material of the secondary scarp (IND) and the western slope sector (C1a) from the Super-Sauze earthflow, the morainic deposits (MOR), the weathered black marls (MAR) and the weathered sandstones (SAN) for the Faucon catchment, were also investigated for comparisons. Analyses have been carried out on undisturbed samples. A detailed geotechnical analysis can be found in O. Maquaire *et al.* (2003) and in J.-P. Malet *et al.* (2002b). The clay fractions of all the materials are mainly composed of illite, chlorite and kaolinite.

Grain-size distributions obtained on the fraction passing the 20 mm sieve help to distinguish the source material: the weathered sandstones (SAN) are sandy gravels, the weathered black marls (MAR) are sandy clays, and the morainic deposits (MOR) are sandy silts (fig. 3C).

For the Super-Sauze earthflow, all matrix samples have a high content of silt and clay (30-40%) and the textural classes range from silty-clay for material C1a to silty sand for IND. C1a is a very cohesive material, composed only of black marls, as IND is composed of a mixture of black marls and moraine (fig. 3D). The grain-size distributions (tab. 1) of the two muddy debris flows DF1 and DF2 deposits cannot be distinguished and are identical to those of the secondary scarp (IND). Unit weights lie in the range of 1140 to 1760 $kg.m^{-3}$ for a specific density ρ_s between 2620 and 2710 $kg.m^{-3}$. Atterberg consistency boundary thresholds (table 1) classify the material as inorganic clays with low plasticity (Ip=13-16%). The liquid limit threshold is much higher for C1a than for IND.

For the Faucon debris flow deposits, the percentage of fine elements (<0.050 mm) does not exceed 7% for LTF5 (source area), but is as much as 30% for LTF1 deposit. According to the classification of I. Bonnet-Staub (1998), LTF5 is classified as a granular debris flow, whilst LTF1, LTF2, LTF3 and LTF4 are classified as muddy debris flows. The deposits are considered as inorganic silt with low plasticity (IP 7-8%). A liquid limit threshold of about 25% is observed.

	Grain-size distribution				Unit weight		Atterberg parameters			Herschel-Bulkley parameters (*)		
	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	γ_d (kg.m^{-3})	γ_{sat} (kg.m^{-3})	W_p (%)	W_L (%)	I_p (%)	τ_c (Pa)	κ (Pa.s^{-1})	(n)
Debris flow												
DF1/DF2	9	24	35	32	1200	1700	15	30	15	25	20	0.34
LTF1-4	6	20	30	44	1250	1630	19	26	7	12	9	0.37
LTF5	3	4	33	60	1220	1610	16	21	5	/	/	/
Source material												
C1a	15	22	25	38	1760	2140	16	32	16	210	130	0.43
IND	10	29	31	30	1220	1790	17	33	16	60	45	0.37
MOR	9	12	38	41	1160	1590	19	30	11	20	5	0.35
MAR	12	14	37	37	1180	1710	21	29	8	105	100	0.31
SAN	5	11	37	47	1140	1650	17	25	8	15	3	0.40

* values for a total solid fraction ϕ of 0.45

Table 1 – **Geomechanical and rheological characteristics of the debris flow deposits and the source materials**.

Tableau 1 – ***Caractéristiques géomécaniques et rhéologiques des écoulements et des matériaux sources****.*

Rheological parameters influence the debris flow runout models significantly (Rickenmann and Koch, 1997). Numerous studies have demonstrated that the behaviour of fine-grained flows is mainly guided by the muddy matrix, which acts as a lubricant, rather than the blocks or debris carried (Coussot and Meunier, 1996). At the opposite, in the case of coarse-grained flows where rheology evolves as mixture agitation, grain concentration, and fluid-pressure change during flow initiation, transit and deposition (Takahashi, 1991; Iverson, 2003), simple constitutive relations (Bingham, Herschel-Bulkley) are not able to capture the complex grain-grain and water-grain interactions controlling these flows.

In clay-shale basins, the debris flow matrix is characterized by a high fine content. For this reason, muddy debris flows occurring in Sauze and Faucon were considered as homogeneous fluids including a yield stress due to the colloidal fraction. We therefore performed a rheological characterisation by parallel-plate rheometry on the <400 µm-fraction, by inclined-plane tests on the <20 mm-fraction, and by analysing at the field scale the shape of the deposit at stoppage by using the relation proposed by P. Coussot *et al.* (1996), taking into account the asymptotic flow depth and the shape of the lateral levee. Due to limitations in the experimental devices, the range of shear rates γ (0.02 s^{-1} to 18,700 s^{-1}) used in this study is two to three times higher than that met with this type of flow in the field (O'Brien and Julien, 1988). Yield stress of the slurry represents the stress at which a static viscoplastic fluid begins motion. Yield stress for typical debris flow material spans the range 10^1 to 10^5 Pa (Coussot, 1997). Herschel-Bulkley consistency of the sediment was only determined by rheometry and back-analysis. A detailed analysis of the rheological properties can be found in J.-P. Malet *et al.* (2003b).

Over the range of shear rates under consideration, all the materials exhibit a viscoplastic behaviour well represented by a Herschel-Bulkley constitutive equation. Herschel-Bulkley parameters (τ_c, κ) increase with the total solid fraction ϕ (ratio of solid volume to total volume), with an Herschel-Bulkley exponent n between 0.17 and 0.40. The yield stress and the consistency varied from 1 to 960 Pa and from 1 to 170 Pa.s^{-1} respectively (fig. 4B, 4C). For total solid fractions between $\phi=0.30$ and $\phi=0.60$ the yield stress may vary by as much as three times, whilst the consistency varies only by twice as much. Laboratory results are consistent with those estimated based on the deposit form of the levees at stoppage and those back-calculated. Values fall within the margin of error specified by P. Coussot (1997) who indicates that the difference in the yield stress estimation using several methods lies between 10 and 25%.

For the Super-Sauze earthflow, rheological parameters clearly distinguish the two types of material in the debris source area: the cohesive silty-clayey matrix (C1a) shows high yield stress and consistency, and the silty-sand matrix (IND) displays lower rheological characteristics. This means that a higher volume of water is necessary to initiate a fluid behaviour in C1a material than in IND material. Combined with the hydrological and geotechnical characteristics, it appears that the main potential source of debris is therefore the eastern part of earthflow (fig. 3B) in the IND material.

For the Faucon catchment, rheological characteristics of the surficial deposits have to be put in relation with the grain-size distribution: clay-poor weathered sandstones (SAN) provide the weakest yield stress (2-30 Pa) while the clay-rich weathered black marls (MAR) provide the highest (14-800 Pa). This indicates that the entrainment of weathered black marls during a debris flow event (scouring) will increase the yield stress and the consistency of the bulk material.

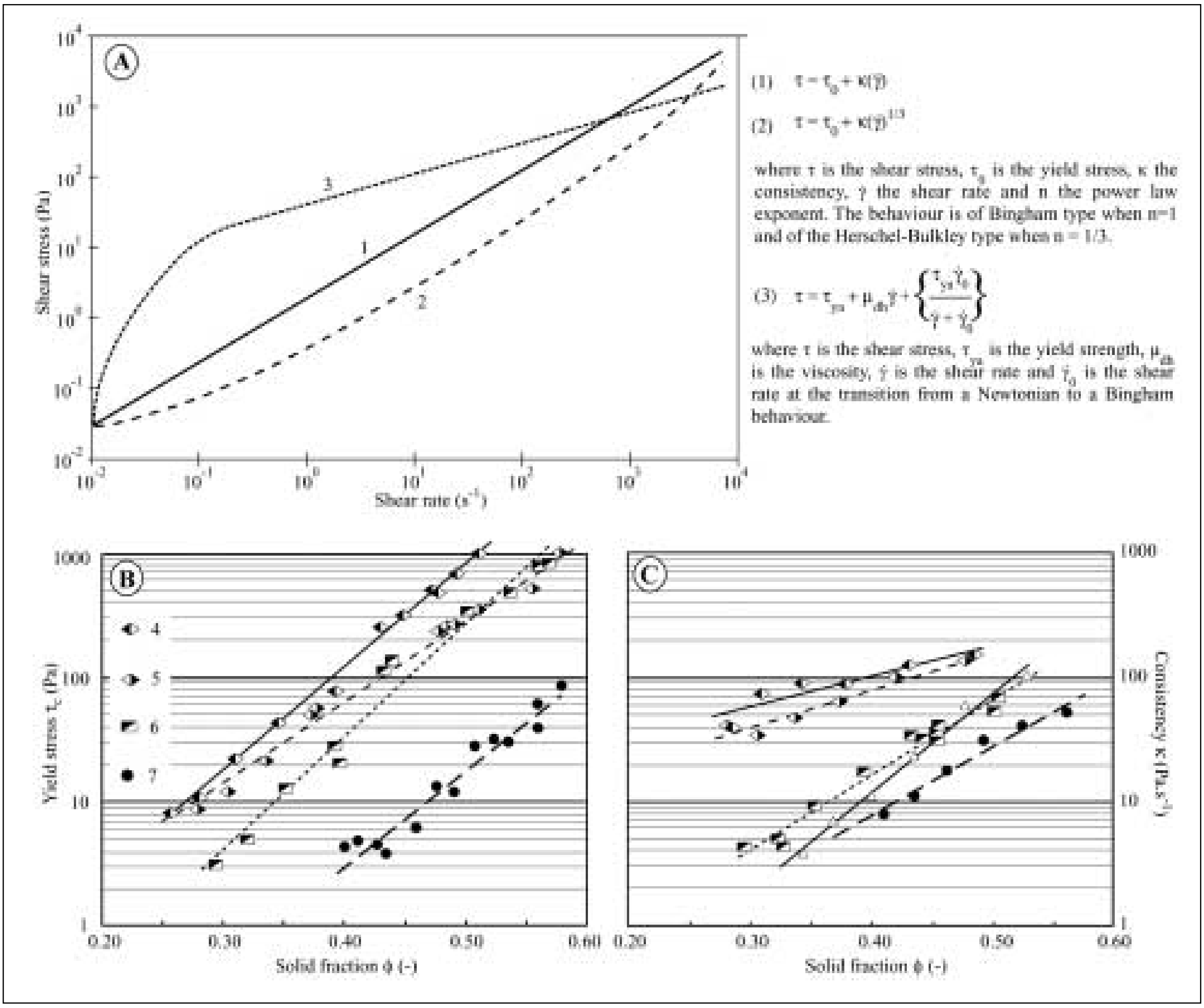


Fig. 4 – **Rheological behaviour of the debris flow deposits an the source material**. A: Typical flow curves of the three rheological models and constitutive equations; B, C: variation of the rheological properties (yield stress, τ_c, consistency, κ) as a function of the total solid fraction. 1: Bingham rheology; 2: Herschel-Bulkley rheology; 3: bi-linear rheology; 4: C1a material; 5: IND material; 6: DF1/DF2 deposit; 7: LTF1 deposit.

*Fig. 4 – **Comportement rhéologique des dépôts de laves torrentielle et des matériaux sources**. A : courbes d'écoulements typiques de trois modèles rhéologiques ; B, C : variation des propriétés rhéologiques (seuil d'écoulement, τ_c,* consistance, *κ) avec la concentration volumique solide. 1 : modèle rhéologique de Bingham ; 2 : modèle rhéologique de Herschel-Bulkley ; 3 : modèle rhéologique bi-linéaire ; 4 : C1a ; 5 : IND ; 6 : COU99 ; 7 : FAU.*

Mobility analyses and calibration of the runout model

Before predicting the mobility of the debris in the torrent streams in order to propose hazard scenarios on the fans, we need to evaluate if the Hershel-Bulkley rheology and the BING code are able to replicate field observations.

A sensitivity analysis of the model has demonstrated that the rheological parameters have a great influence on the modelling results (Imran *et al*., 2001; Malet, 2003). For instance, a variation of 50% of the yield stress values leads to a mean change of 50% on the deposit thickness, while a variation of 50% of the consistency introduces changes up to 20%. Moreover the effect of the rheological parameters depends on local slope gradients. Consequently, the relative influence of the rheological parameters may not be the same for every debris flow event, even if the yield stress seems to be usually dominating. At the opposite, the sensitivity of the model to variations of the input volume is important, and significant for a volume variation of only 10% (Malet, 2003; Remaître *et al.*, 2003a). Finally model outputs are very sensitive to the mesh configurations for low resolution calculations (number of mesh < 200) and insensitive to the mesh configurations for high resolution calculations (number of mesh > 200); in this latter case, a variation of the mesh size of 25% leads to an error on the theoretical computed flow thickness of less than 5% (Malet, 2003).

According to these results, the performance of the runout model has been evaluated by analysing the mobility of three events: the small debris flow initiated in the C1a material, the DF2 muddy debris flow initiated in IND material, and the 1996 debris flow in the Faucon stream (fig. 5). As the initial profile of the failed mass is assumed to be parabolic, the initial geometry of the debris includes the length of the failed mass and the maximum thickness of the initial deposit. Therefore, a volume per unit width of respectively 15 m^2, 340 m^2 and 5,000 m^2, was simulated for the small muddy debris flow (fig. 5A), the DF2 muddy debris flow (fig. 5C), and the Faucon muddy debris flow (fig. 5D) respectively. The channel bed topography is also given as an input initial condition. It is important to note that check dams have been included in the path profile of the Faucon stream. Rheological parameters corresponding to the observed total solid fraction of the events (Malet *et al.*, 2003a) were used as input values.

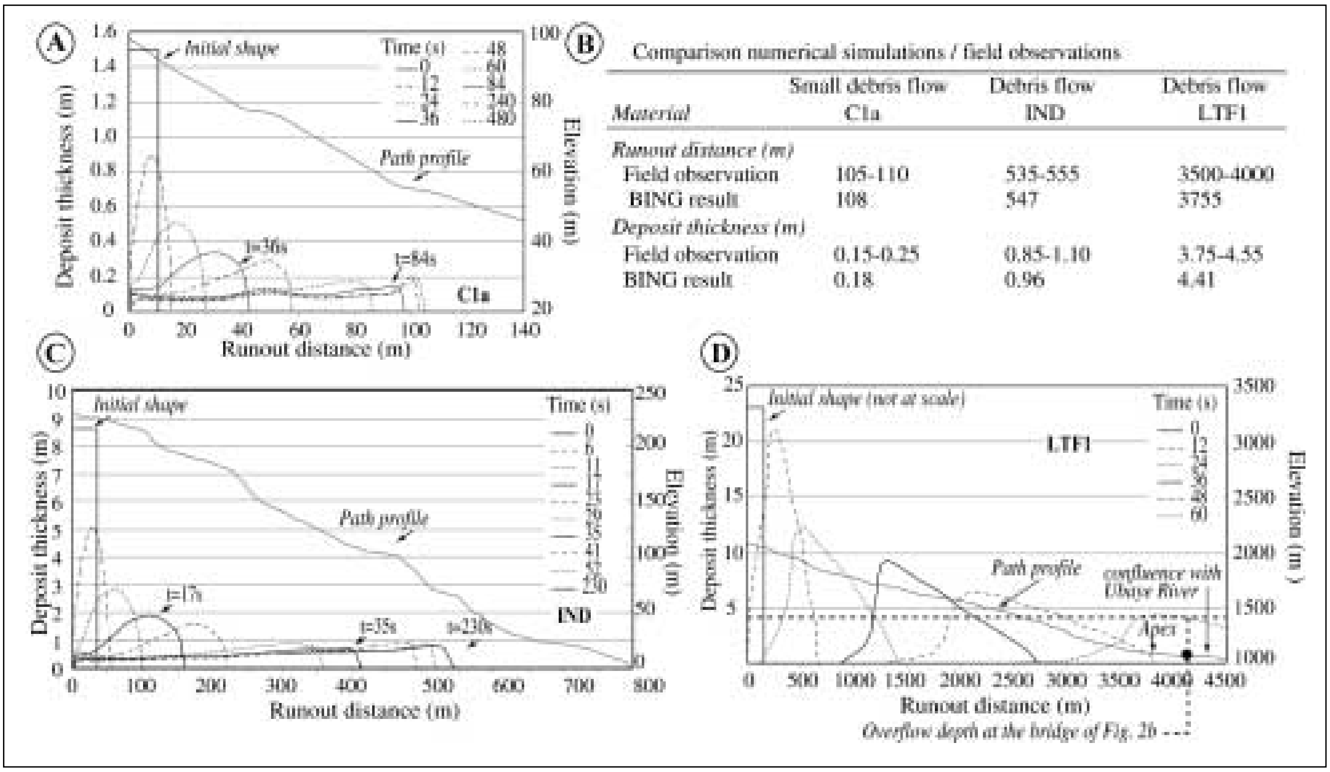
Outputs consist of the front location, the front velocity and the deposit thickness with time. The runout distance and the final deposit depth at stoppage were used as criteria to assess the validity of the numerical simulations. For the Faucon study case, the runout distance at stoppage could not be used because the 1996 debris flow reached the Ubaye River. Therefore only the flow depth, observed at a bridge in the middle part of the fan, was used. The simulations were performed without any calibration procedure.

Results indicate that the runout code matches the observed geometry fairly well for the flow thickness and the runout distance (fig. 5B) whatever the initial source volume. Figures 5A, 5C and 5D show the runout and deposit thickness as a function of variable yield stress and consistency from several simulations. The largest runout distances and thinnest deposits are observed at lowest yield stress. Consistency played a minor role in deposit thickness and only affected runout distance at the lowest yield stress, as represented by the large span of runout distances predicted by BING. The best-fit distances and deposit depths are obtained for yield stress and consistency consistent with those estimated using the laboratory tests. For the three events, the relative error ranges between 2 and 8% for the runout distance, and between 12 and 28% for the deposit thickness. This error is acceptable according to the relative error associated with the determination of the rheological parameters.

These results confirm the fact that the Hershel-Bulkley rheology and the BING code are able to replicate field observations for consistent total solid fractions. Nevertheless, if the mobility analyses predict fairly well the runout

Fig. 5 – **Flow modelling and mobility analyses of three muddy debris flows events**. A: evolution of the geometry during propagation and final deposit shape (thickness, runout) for the small event in C1a material at Sauze; B: model numerical simulations and field observations; C: evolution of the geometry during propagation and final deposit shape (thickness, runout) for the DF2 debris flow in IND material at Sauze; D: evolution of the geometry during propagation and final deposit shape (thickness, runout) for the 1996 debris flow at Faucon.

Fig. 5 – ***Analyse numérique de la mobilité de trois événements de laves torrentielles à matrice cohésive****. A : évolution de la géométrie pendant la propagation et forme finale du dépôt (épaisseur, distance de parcours) pour un événement de faible volume dans le matériau C1a à Sauze ; B : comparaisons entre les simulations numériques et les observations ; C : évolution de la géométrie pendant la propagation et forme finale du dépôt (épaisseur, distance de parcours) pour la lave torrentielle DF2 dans le matériau IND à Sauze ; D : évolution de la géométrie pendant la propagation et forme finale du dépôt (épaisseur, distance de parcours) pour la lave torrentielle de 1996 à Faucon.*



Material	Small debris flow C1a	Debris flow IND	Debris flow LTF1
Runout distance (m)			
Field observation	105-110	535-555	3500-4000
BING result	108	547	3755
Deposit thickness (m)			
Field observation	0.15-0.25	0.85-1.10	3.75-4.55
BING result	0.18	0.96	4.41

distances and the lobe geometries, the velocity of the flow is three orders of magnitude higher than that measured in the field. This may be explained by an underestimation of the real consistency mobilised during shearing, which must be three orders of magnitude more, and the influence of the pore pressure ratio fluctuations which is not taken into account in the model (Van Asch *et al.*, 2004). Moreover , in the case of the Faucon stream, it was stated that the initial volume coming from the source area was about 5,000 m^3 and that the debris flow slurry volume increases during the runout until reaching a value of 100,000 m^3. As it is not possible to impose a scour per metre value at the boundaries of the BING model, the input volumes used for the simulations are in agreement with the deposit volumes, but not the source volume. The potential energy of the flow is therefore highly overestimated by assuming all the deposited mass was initiated at source (Remaître *et al.*, in press).

Nevertheless, as a good agreement between model predictions and reality has been observed for the runout distances and the deposit thickness, the BING code can be used to simulate torrential hazard scenarios.

Modelling scenarios

The evaluation of torrential hazard scenarios on alluvial fans (in terms of runout distances reached by the debris, and deposit depths) is of prime interest in mountainous areas. The relevance of this problem in the Ubaye valley has been demonstrated by the activity of the torrential streams, and by the mudflows and debris flows induced by the reactivation of the La Valette earthflow (Colas and Locat, 1993). In order to reduce debris flow hazard, it is common to couple structural and non-structural protections, such as zoning of the hazard-prone areas. Protection plans require the definition of scenarios that can be assessed by means of simulations with numerical models. In our case the potential volumes of debris needed to reach the apex of the alluvial fan or the confluence of the Ubaye River have been estimated.

Several numerical simulations were performed with the BING code (1) by using the geomechanical and rheological parameters employed in the debris flow mobility analysis, (2) by changing the volume of released sediment (the volume released at the beginning of the calculation corresponds to a volume of solid debris and water), and (3) by changing the total solid fraction ($\phi = 0.40$, $\phi = 0.45$, $\phi = 0.50$). As a first approximation no scouring of the channel and the banks due to the debris flow was considered.

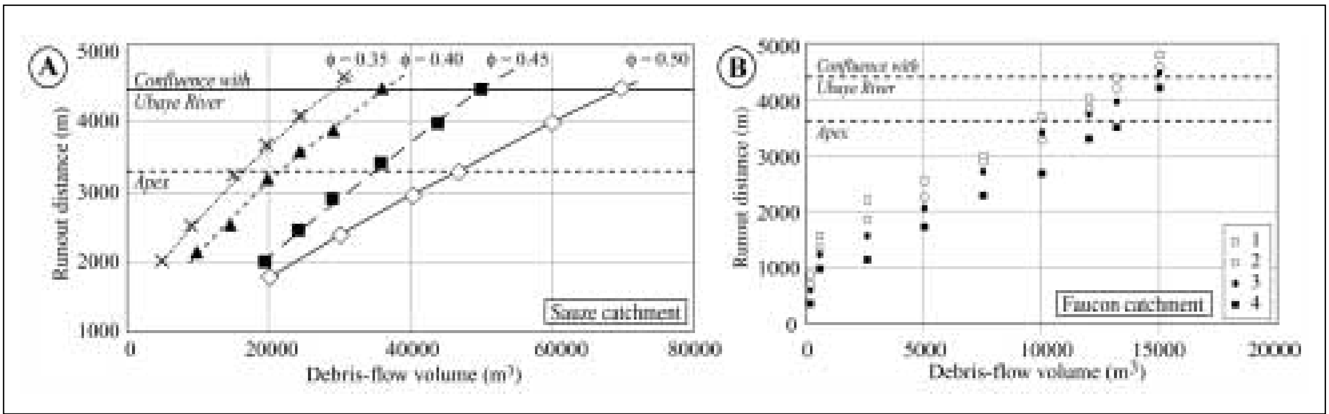
We adjusted the volume of input debris with the assumption that the deposits at stoppage must be at least 0.50 m-thick. Usually, in case of debris flow accumulation, for hazard assessment and mapping (Petrascheck and Kienholz, 2003), this thickness corresponds to the minimum value at which the push prompting and damage effect on the exposed structures are effective.

Figure 6A shows the results of the scenario analysis. The graphical representation is the following: the lower horizontal axis shows the volume of sediment (solid debris + water) that propagated along the channel, the upper horizontal axis corresponds to the volume of solid debris for the different total solid fractions ϕ. As presumed, the runout distance increases with the volume of debris. The same relationship can be found between the total solid fraction and the volume.

For total solid fractions consistent with those generally observed in muddy debris flows (Coussot and Meunier, 1996), the minimal volume of sediment necessary to reach respectively the apex and the confluence with the Ubaye River, ranges between 30,000 and 50,000 m^3 for the Sauze torrent, and between 15,000 and 20,000 m^3 for the Faucon

Fig. 6 – **Runout modelling scenarios for the Sauze and Faucon alluvial fans**. A: Sauze alluvial fan. Estimation of the debris volume necessary to reach the apex of the torrent and the Ubaye River confluence for different total solid fractions (IND material); B: Faucon alluvial fan. Estimation of the debris volume necessary to reach the apex of the torrent and the Ubaye River confluence for the different surficial formations (total solid fraction $\phi = 0.45$). 1: sandstone; 2: deposits of the 1996 debris flow at Faucon; 3: moraine; 4: black marls.

*Fig. 6 – **Scénarios de lave torrentielle par modélisation numérique pour les cônes de déjection du Sauze et de Faucon**. A : cône de déjection du torrent de Sauze. Estimation du volume de matériau nécessaire pour atteindre l'apex et la confluence avec l'Ubaye pour différentes concentrations volumiques solides (exemple du matériau IND) ; B : cône de déjection du torrent de Faucon. Estimation du volume de matériau nécessaire pour atteindre l'apex et la confluence avec l'Ubaye pour différentes formations superficielles des zones sources (concentration volumique solide $\phi = 0.45$). 1 : flysch ; 2 : matériaux de la lave torrentielle de 1996 ; 3 : moraine ; 4 : marnes noires.*



torrent. In the Faucon stream, it is worth noting that in 1996 the debris source volume was approximately only 5,000 m^3, so if scouring had not occurred, the debris flow would not have reached the alluvial fan.

For the Sauze torrent, a maximum final deposit thickness of 0.55 m and 0.40 m are predicted by the model respectively on the apex and at the confluence. Assuming total solid fractions of 0.45, the volume of debris that has to fail in the debris source area ranges from 21,000 to 29,000 m^3. Coupled seepage and stability analyses were carried out to estimate the stability of the earthflow (Malet and Maquaire, 2003). Conditions in the debris source area are close to failure for average pore-water pressures, and for residual strength (Maquaire *et al*., 2003; Malet *et al*., 2003a). A small excess of water (for instance snowmelt) can therefore initiate failure. Results of the scenario analyses show that hydrological conditions able to initiate failures of 21,000 to 29,000 m^3 are attained for a cumulative input of water of 65 mm (over a 3-day long period) corresponding to a 25-year return period rainfall. To improve the estimates on the failed volume, some attention should also be given to the possibility of moisture content change with movement, due to (1) the dissipation of the pore pressure due to the grain-size segregation and the development of a debris flow head consisting mainly of gravel (Iverson, 2003) and (2) the dilution of the debris flow with surface water.

For the Faucon torrent, we can suppose that small failed volumes require an additional mechanism to generate long runout distances. Runout distance differences between the four types of surficial formations have to be considered in relation with their rheological characteristics. The material with the weakest yield stress (in our case the weathered sandstones, SAN) displays the highest runout distance, but not the highest deposit thickness. So increases in yield stress (by addition of a surficial deposit in the mixture by scouring) result in shorter runout distances and thicker final deposits. Additional data must be obtained on artificial mixtures of these three main surficial deposits in order to find the mixture that presents the most favourable characteristics for flowing *i.e.* the weakest yield stress.

Conclusion

A combination of several analyses (geomorphological survey, sedimentological analyses, rheological tests, and numerical modelling) provides valuable data for a first step in the development of a methodology for assessing hazards along muddy debris flow torrents and alluvial fans. The Faucon and Sauze case histories outline significantly the importance of field observations and rheological characterization to calibrate numerical models. The proposed methodology allowed the evaluation of realistic hazard scenarios for such instabilities.

Grain-size distributions show that all the debris flow deposits can be categorized as muddy debris (more than 20% of clay and silts). In the case of the Faucon debris flow, comparisons between the source materials and the surficial deposits showed a clear difference between the initiation area and contributing areas. Several rheological tests have demonstrated that materials derived from black marl formations (C1a, IND, MAR), the moraine deposits and the weathered sandstones exhibit a rheological behaviour in simple shear which can be described by a Herschel-Bulkley model.

A dynamic debris flow model has been used to estimate runout scenarios. The BING code enables representation of the dynamics of the slurries without the use of parameter calibration. A good agreement between model predictions and reality has been observed for the flow thickness and the runout distance.

Therefore a scenario analysis has been performed to estimate the volume of material that has to fail in the source area to reach either the apex or the downstream part of the alluvial fans of the Sauze and Faucon torrents. The numerical simulations have showed that the debris flow volume must be at least 30,000 m^3 for the Sauze torrent and 15,000 m^3 for the Faucon torrent in order to reach the alluvial fan. Additional computation with several types of source materials showed that the rheological parameters of each sediment influence debris flow runout distances and deposit thickness.

Major efforts should be devoted to the development of runout models capable of taking into account channel-bed scouring and variation of rheology with distance and time, especially for debris flows triggered in heterogeneous watersheds. Moreover, hazard scenarii could be ameliorated by delineating high, medium and low hazard areas on the alluvial fans, on the basis of deposit thickness, by considering natural damming, obstruction of the river course, occlusion or destruction of bridges, or damage to structures. This was not the focus of this study, but the work is actually in progress by using two- or three-dimensional spreading models.

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