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Study of a debris-flow event by coupling a geomorphological and a rheological investigation, example of the Faucon stream (Alpes-de-Haute-Provence, France)

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ABSTRACT: The incorporation of surficial deposits during a debris flow may change its mechanical behavior. This is illustrated by a morphological survey of the Faucon stream in the Barcelonnette basin, Alpes-de-Haute-Provence (France), where a large debris flow occurred in the summer of 1996. Grain-size distribution shows that this debris flow can be characterized first as a granular and then as a muddy flow. The results of rheological tests show that the flow behavior can be described using a Herschel-Bulkley constitutive equation. The rheological response of several artificial mixtures of surficial deposits (sandstones, moraines, weathered black marls) were investigated using either a parallel-plate rheometer, a coaxial rheometer, slump tests, or an inclined plane for the purpose of comparison with the debris flow deposits. Yield stress and viscosity increased with the proportion of black marls in the artificial sediment mixture. The artificial sediment mixture presenting the closest behavior to the 1996 debris flow is made of black marls (20%), moraines (30%) and sandstones (50%). Both the result of this rheological investigation and geomorphologic field evidence indicate that the debris flow scoured the middle and the lower part of the Faucon stream.

1 INTRODUCTION

Debris flows in mountainous areas can transport large quantities of sediment downslope, producing complex distributions of deposits and eroded surfaces along their flowpaths. Ascertaining the risk from debris flow calls for a multidisciplinary approach combining geotechnical engineering, hydrology, climatology, geology, sedimentology, geomorphology and rheology. The triggering mechanisms (Johnson & Rodine 1984, Johnson & Sitar 1990, Iverson et al. 1997, Tognacca & Bezzola 1997, Wieczorek et al. 1997, Bonnet-Staub 1999) and the behavior of debris flows (Pierson & Costa, 1987, Major & Pierson 1992, Coussot & Meunier 1996, Iverson 1997, Iverson & Vallance 2001) are well known, yet it is still difficult to define their temporal and spatial occurrence. The literature regarding debris flows does not take sufficient account of contributing mechanisms like channel scour (Hungr et al. 1984, Pierson et al. 1990, Fannin & Rollerson 1993, Jakob et al. 1997, Berti et al. 1999, Jakob et al. 2000, Arattano 2000, Pérez 2001). Nevertheless channel scour may be responsible for major differences in sediment accumulation between the initiation and deposit areas. Debris flows can increase progressively to 10 - 15 times their original volume because of the loose material they carry (Vandine & Bovis 2002). Moreover, in a watershed with various lithologies, the rheological response of the surficial deposits will be variable and the debris flow's run-out characteristics (velocity, discharge, spreading) evolve according to the evolving agitation, the pore-fluid pressure (Iverson & Vallance 2001), and the rheological parameters of the surficial deposits incorporated into the flow by scouring and/or erosion phenomena.

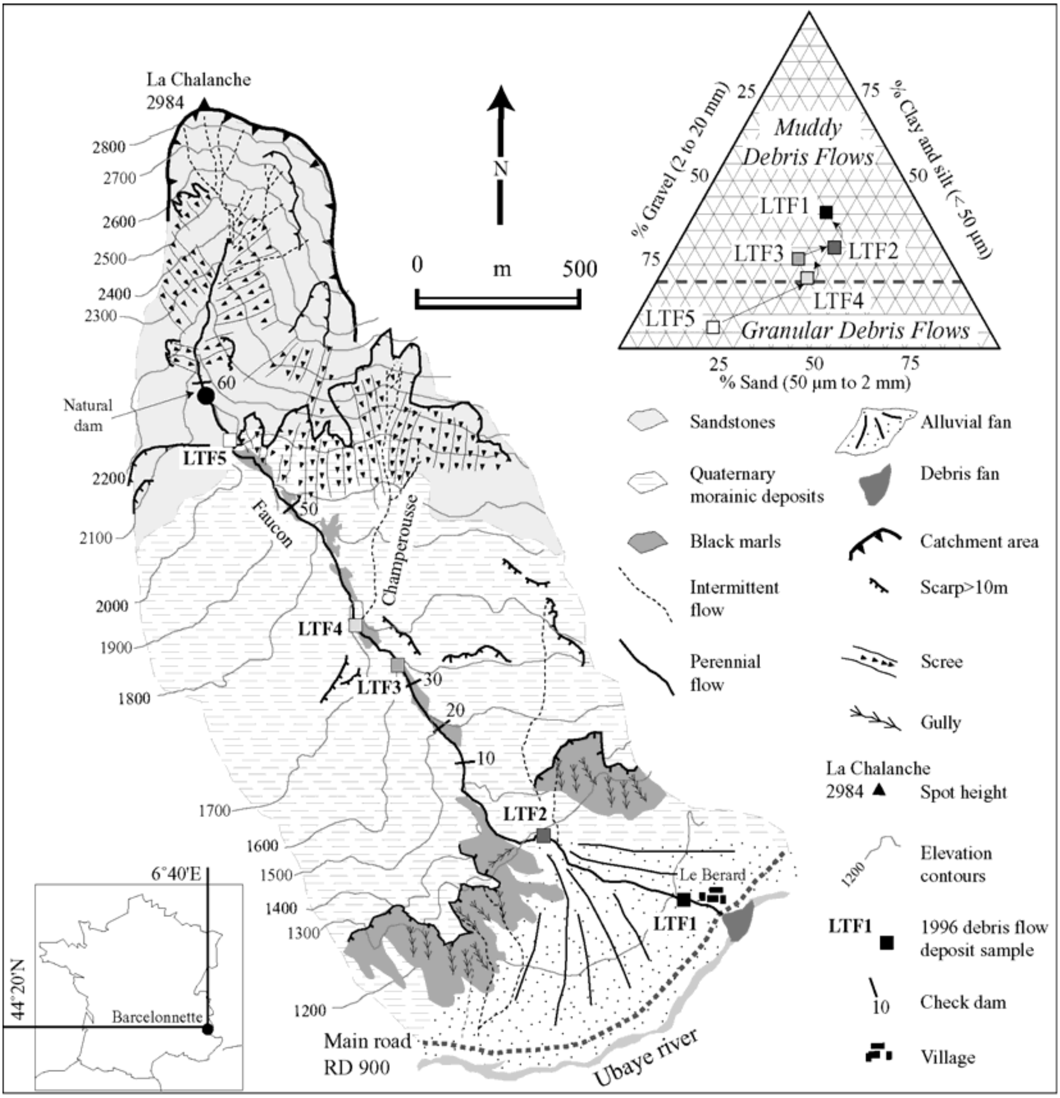

Figure 1. Morphological sketch of the August 19, 1996 debris flow in the Faucon stream and grain-size distribution of five samples of the 1996 debris flow.

On August 19, 1996 a large debris flow occurred in the Faucon stream after a violent thunderstorm affected the catchment basin. The velocities (approximately 5 $m \cdot s^{-1}$) were back-calculated using the forced vortex equation (Hungr et al. 1984) and multiplied by the cross-sectional area, obtaining peak discharge estimates ranging from 90 $m^3 \cdot s^{-1}$ to 110 $m^3 \cdot s^{-1}$. Approximately 100,000 m^3 of sediment was deposited during this event (Remaître et al. 2002). A study has been carried out to define: (i) the sedimentological characteristics of the debris flow deposits and the surficial deposits, (ii) the behavior of the debris flow, and (iii) the artificial mixture of surficial deposits which present the same characteristics as the August 19, 1996 debris flow.

2 STUDY AREA

The Faucon catchment (10.5 km^2 in area, 7 km in length) is on the south-facing slope of the Barcelonnette basin (Alpes-de-Haute-Provence, France) (Fig. 1), which slopes from 1100 to 3000 m altitude. The upper rock crest is formed by two massive sheet thrusts (Parpaillon and Autapie), made up of limestones and sandstones. The Ubaye river, which drains the basin, has carved out 13,000 ha of autochthonous black marls. 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). In 1996 there was an important debris flow in the Faucon stream (Fig. 1), a tributary of the Ubaye river. The mean slope of the Faucon torrent is 20° - 25°, reaching 80° on the highest stretches of the catchment basin. Seventy-six check dams were built during the 1890s to prevent flooding but only half are still effective. The rocky substratum is composed of faulted sandstones and black marls. Quaternary deposits, mostly moraines, scree, and landslide accumulations, are common in the basin. The Faucon torrent has formed a huge fan which spreads across the floor of the Ubaye valley. This extends southward for about 1 km and covers an area of 2 km^2; it has a slope ranging from 6° - 9°. There have been fourteen debris flows in the Faucon stream since 1850 (about one every 10 years for the Faucon, one every 20 years for the other torrents of the Barcelonnette basin).

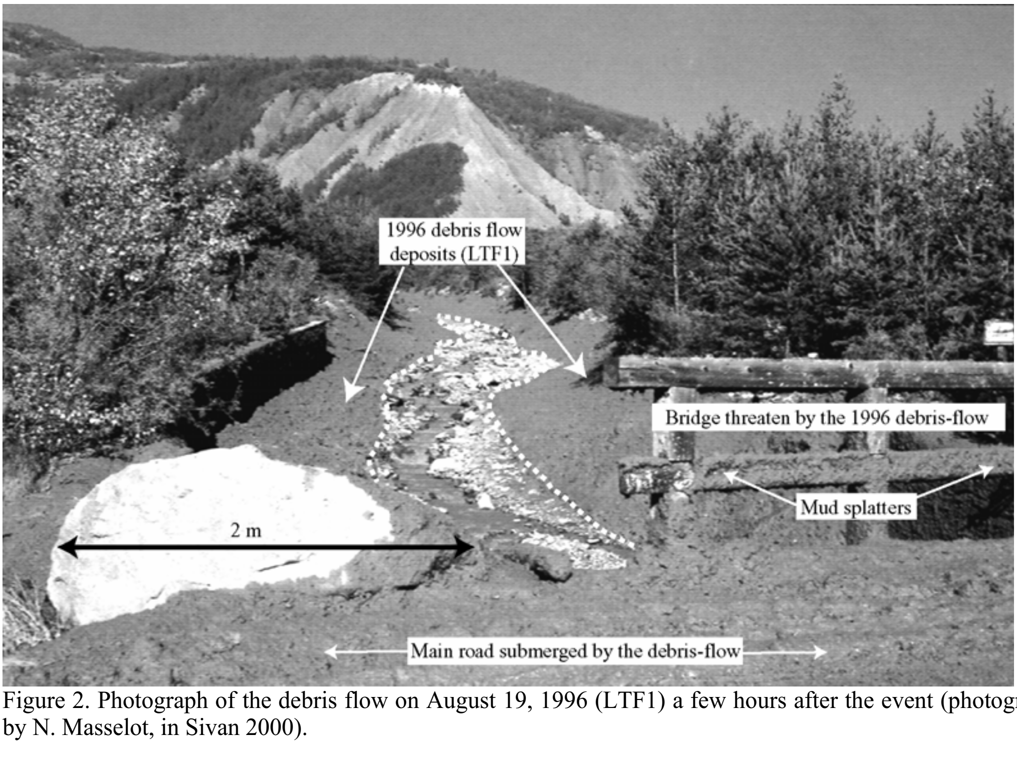

Figure 2. Photograph of the debris flow on August 19, 1996 (LTF1) a few hours after the event (photograph by N. Masselot, in Sivan 2000).

3 MORPHOLOGY AND MATERIAL CHARACTERISTICS

Our study of the initiation and the scour potential of debris flows included a morphological survey, a sedimentologic analysis of the surficial and debris flow deposits and a rheological investigation.

Five samples of the deposits from the debris flow of 19 August 1996 (Fig. 2) and the three main surficial deposits were described and analyzed.

3.1 *Morphological and sedimentological analysis of the 1996 debris flow*

There are several debris flow deposits in the Faucon stream, labeled LTF (Fig. 1). They consist of large fragments of sandstone and moraine boulders set in a finer gray matrix and overlain by a hardpan which preserves their original shape.

Levees occur along the length of the transport zone; they form discontinuous narrow ridges rising 2-3 m above the surrounding slope on both sides of the channel (Figs 2-3a) and are as much as 100 meters long and 30 meters wide. Surface material consists of various sizes and shapes. Lateral sorting of the debris flow deposit is poor, whereas vertical rough sorting is high. The coarser clasts and boulders are concentrated at the top of the flow surface, producing inverse grading, as observed elsewhere by many authors (Costa 1984, Takahashi 1991, Major 1998, Berti et al. 1999, Hungr et al. 2001). Different bedding types can be observed (Fig. 3b): (i) an indurate stratum corresponding to the flow hardpan; this may be covered by a thin stratum of fine material deposited by a subsequent stream flow, (ii) an alluvial stratum or hyper-concentrated flow stratum, consisting of fine loose material with a high lateral sorting, and (iii) a debris flow stratum with coarser material and debris set in a fine matrix.

Only five deposits of the 1996 debris flow could be studied along the channel. Indeed the French Forest Office cleaned the channel just a few hours after the event. Thus most of the deposited debris had been removed very quickly after the event. The main end-lobe (LTF1), some 70 m long and 5 m wide, was located a hundred meters above the apex. But most of the debris flow spread over the old (before the 1996 debris flow) alluvial fan and joined the Ubaye River (Fig. 1).

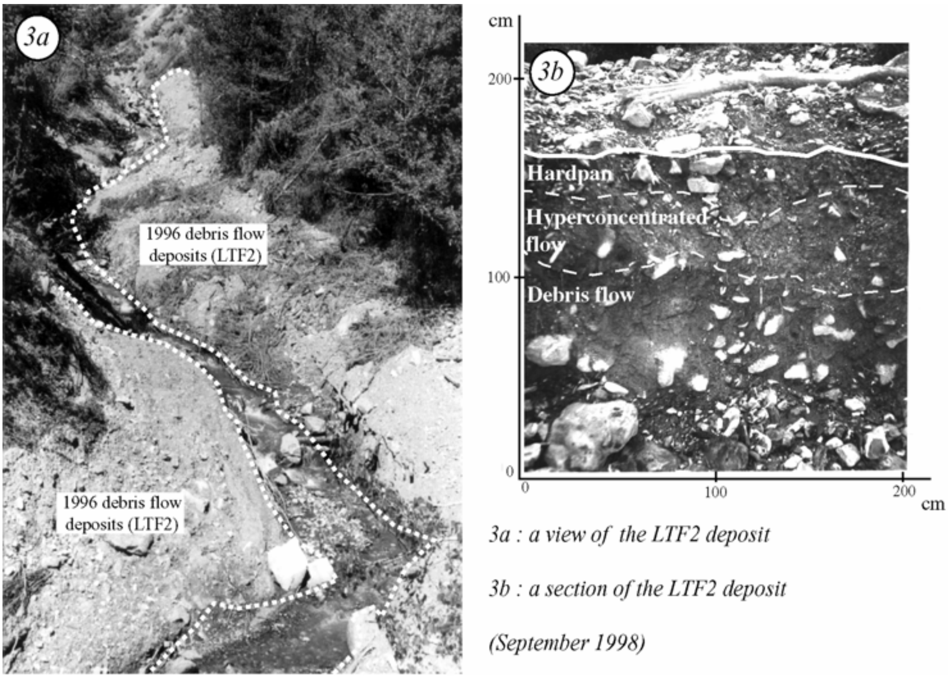

Figure 3. Photographs of (3a) a view of the LTF2 deposit and (3b) a section of the LTF2 deposit.

Five deposits of the 1996 debris flow were sampled (Fig. 1), two in the lower part of the stream near the apex of the Faucon stream (LTF1, 1270 m) and on the debris fan (LTF1, 1200 m), two in the central part of the stream (LTF3, 1620 m and LTF4, 1715 m) in the black marls, and one in the source area located in the sheet thrust (sandstone) (2050 m).

The grain-size distribution obtained from the fraction passing the 20 mm sieve showed that the five samples differed remarkably. The choice of < 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 & Steinwendtner 2000); it represents 55-80% of the weight of the total grain-size distribution. The percentage of fine material (finer than 0.050 mm) did not exceed 7% for LTF5 (source area), whereas it was 30% in the LTF1 deposit (Fig. 4). This fine enrichment is mainly due to the passage of the flow over loose formations in the intermediate reach of the Faucon channel (quaternary moraines deposits and weathered black marls). Grain-size distributions of these surficial formations are given in Figure 5. Bonnet-Staub (1999) compared grain-size distributions (samples < 20 mm) of several debris flow that occurred in the French Alps. Results show that two types of debris flows could be distinguished: (i) debris flow with a granular matrix (clay and silts < 20%), and (ii) debris flows with a muddy matrix (clay and silts > 20 %). According to the classification of Bonnet-Staub (1999), the LTF5 deposit is a granular debris flow, whereas LTF1, LTF2, LTF3 and LTF4 are muddy debris flows. Atterberg limits classify the deposited material as low plasticity inorganic silt (Plastic Index equals 7-8%) with a liquid limit of about 25%.

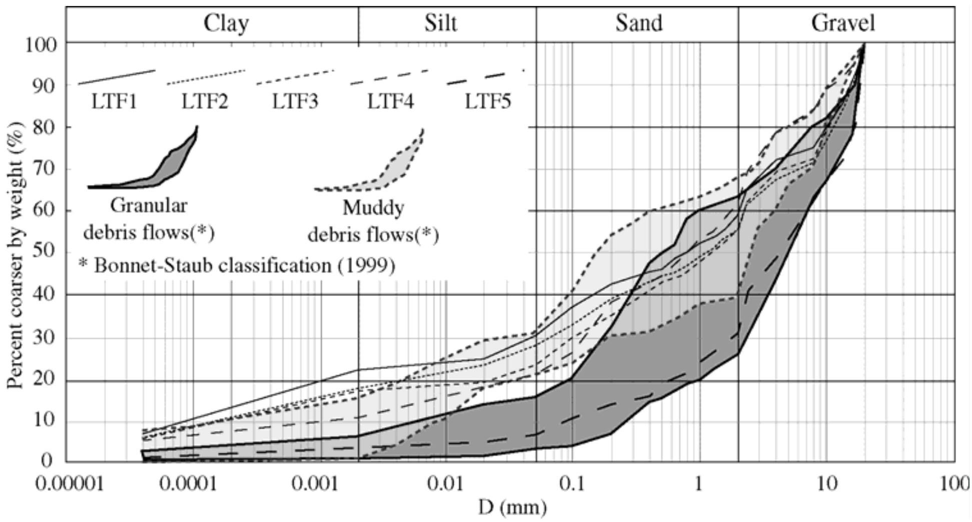

Figure 4. Grain-size distribution of the August 19, 1996 debris flow deposits.

3.2 *Characterization of the surficial deposits and the artificial mixtures*

Petrographic analyses of the five samples showed that the three surficial deposits represent the bulk of the debris flow: weathered black marls, weathered sandstones, and quaternary moraine deposits (Remaître et al. 2002). The object of the laboratory tests was therefore: (i) to find an artificial sedimentary mixture presenting the same characteristics as the 1996 debris flow deposits and (ii) to define the artificial sedimentary mixture with the highest mobility potential.

Several samples of the three types of surficial deposits were analyzed (about 10 for each type of material). The grain-size distribution obtained on the fraction passing through the 20 mm sieve clearly distinguished the three formations: weathered sandstones (SAN) were sandy gravels, weathered black marls (MAR) were sandy clay, and quaternary moraine deposits (MOR) were sandy silts (Fig. 5a). The three materials have approximately the same mineralogy (illite, chlorite and kaolinite) and they are not thixotropic (Malet et al. 2002). We therefore consider that the differences in rheological behavior are due to granulometric characteristics. The three surficial deposits were mixed by weight to obtain twelve artificial mixtures (Fig. 5b).

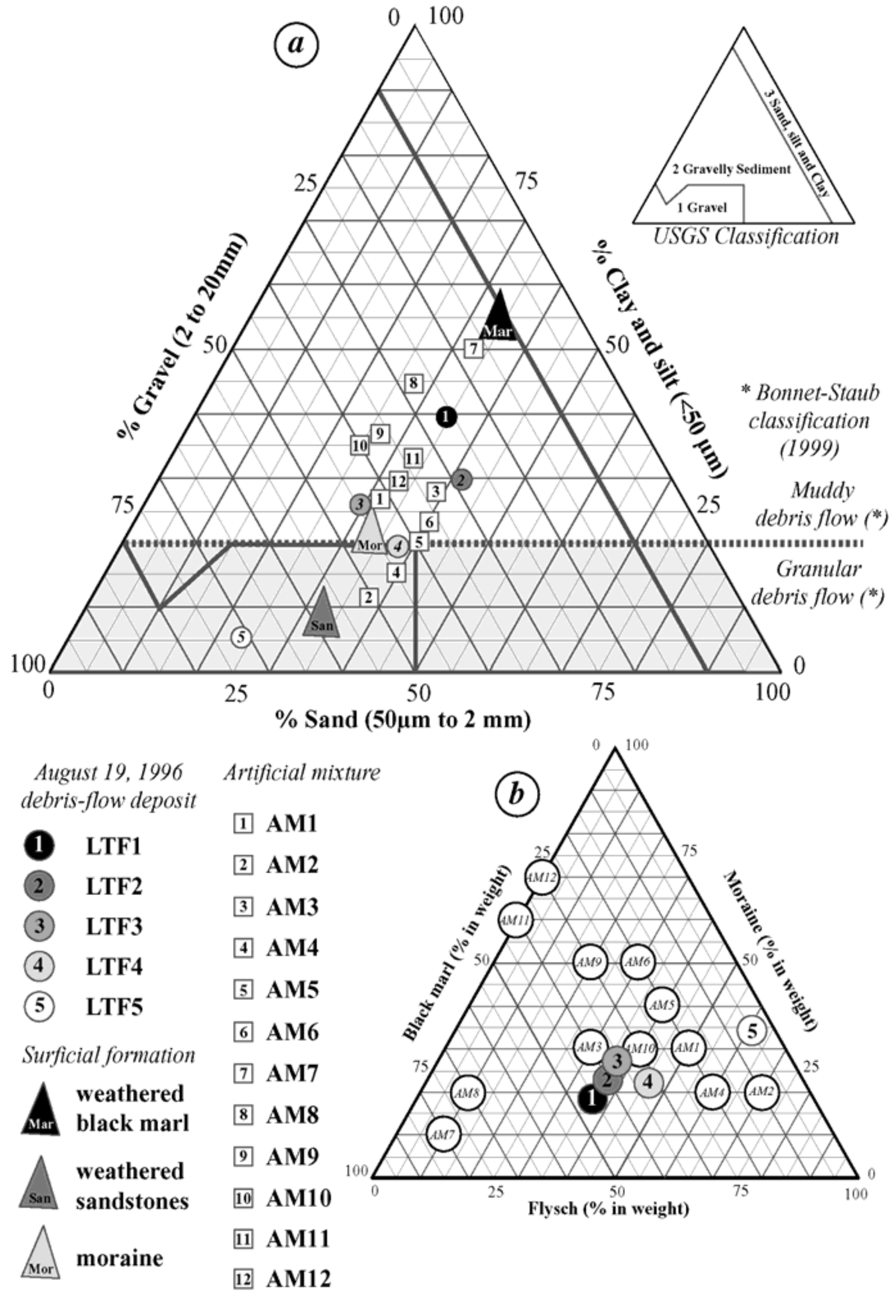

Figure 5. Grain-size (a) and petrographic distribution (b) of artificial sediment mixtures and of the August 19, 1996 debris flow.

The mixture proportions were suggested by investigating: (i) the influence of small variations of mixtures in the central part of the triangle for comparison with the 1996 debris flow deposit, and (ii) the influence of each constitutive material (SAN, MOR and MAR) on the overall behavior of the mixture. We were unable to determine the yield stress by rheometry of mixtures in which the fraction of sandstone was over 70%; the yield stress for these mixtures falls while the shear rate rises. We were therefore unable to reproduce the experimental data with a numeric model.

The grain-size distribution characteristics of the 12 artificial mixtures were plotted and compared with the characteristics of the 1996 debris flow (Fig. 5). The granular debris flow deposit (LTF5) is close to AM2, which consists essentially of weathered sandstones. AM1, AM3, AM5 and AM6 mixtures have characteristics close to the muddy debris flow deposits (LTF1 to LTF4). Results are in agreement with the geomorphological survey; the debris flow was therefore initially granular and subsequently muddy owing to fines enrichment as the flow passed over the outcropping black marls and the quaternary moraine deposits.

4 RHEOLOGICAL TESTS

4.1 *Methodology*

The direct determination of the behavior of debris flow material with the help of rheometers is faced with the irretrievable problem that they generally contain particles of various sizes including big boulders (Coussot & Meunier 1996). Numerous studies have shown that the behavior of fine-grained debris flows is mainly guided by the muddy matrix rather than the blocks carried (Pierson 1986, O'Brien & Julien 1988, Major & Pierson 1992, Coussot & Meunier 1996). In the case of coarse-grained (granular) debris flows where rheology evolves as mixture agitation, grain concentration, and fluid-pressure change during flow initiation, transit and deposition (Iverson 1997, Iverson & Vallance 2001), simple constitutive relations (Bingham, Herschel-Bulkley) are not able to capture the complex grain-grain and water-grain interactions controlling these flows (Hungr 2000).

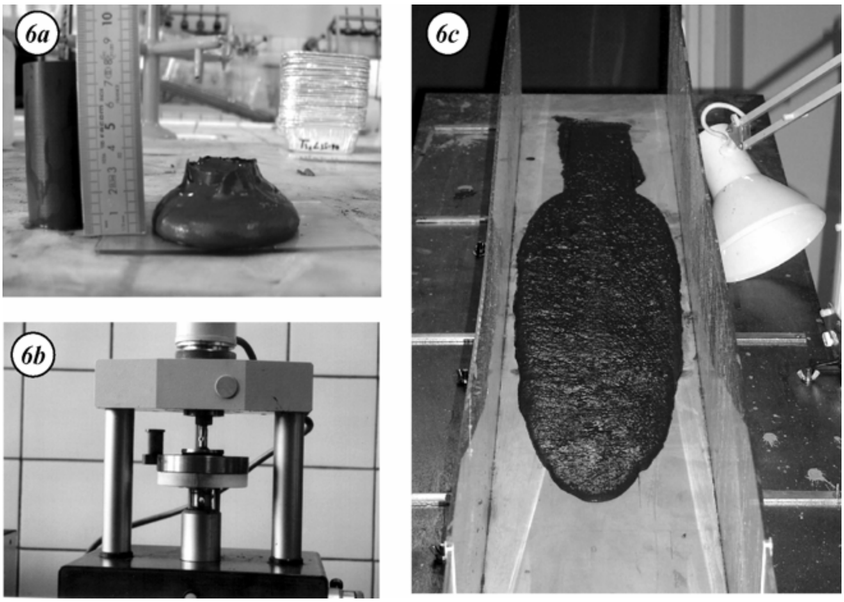

Figure 6. Photographs of the three rheological tests: (6a) slump Test, (6b) parallel-plate rheometry, (6c) inclined plane.

Grain-size distribution analyses of the 1996 debris flow show the muddy character of the flow (more than 20% of clay and silt). In such a case of fine-grained sediments, the presence of colloidal fractions may introduce yield stress (Major & Pierson 1992). For these reasons, some specific rheological analysis for fine-grained debris flow were carried out on debris flow and surficial deposits samples, using either a parallel-plate rheometer and a coaxial rheometer on the < 400 µm fraction, slump tests and a inclined plane for the < 20 mm fraction.

Our main objectives were to define the behavior of: (i) the 1996 debris flow, (ii) the artificial mixtures with the weakest yield stress and thus the highest mobility potential, and (iii) the artificial mixture having the same behavior as the 1996 debris flow.

More details on the methodology we used are contained in Malet et al. (2002) and in Malet et al. (in press). Different rheological investigations (Fig. 6) were used to obtain a good representation of the grain-size distribution (rheometrical tests, slump tests, inclined plane tests). For these tests, samples of LTF1 and LTF2 were mixed together. Indeed, we need a significant volume of material in order to perform all the tests. Moreover, grain-size characteristics of LTF1 and LTF2 are very close.

Several physical explanations for viscoplastic behavior have been suggested; the behavior of muddy debris flows is usually described using empirical models. Three viscoplastic models were tested (Bingham, bi-linear and Herschel-Bulkley) for all the materials and for various total solid volume fractions. It should be noted that yield stress estimated with the two rheometric geometrical forms (parallel-plate, cone-plate) are very similar ($R^2 = 0.98$) (Malet et al. 2002). The estimation of yield stress by rheometry, slump test and inclined plane gave more dispersed results. For these investigations, relative error varied between ± 20% (Malet et al. in press).

4.2 *Behavior of the 1996 debris flow*

Given that our debris flow fluids were slightly thixotropic (Malet et al. 2002) and the shear rate used was sufficiently low, the yield stress (τ_c) obtained by fitting models is a close estimate of the real yield stress (Coussot & Piau 1994). The LTF deposit exhibited a visco-plastic behavior for all shearing speeds and was well fit by a Herschel-Bulkley model ($R^2 = 0.85$). Herschel-Bulkley parameters (τ_c, κ) decreased with the total solid volume fraction and n varied between 0.17 and 0.40. The yield stress ranged from 1 to 87 Pa and viscosity from 1 to 52 Pa·s.

4.3 *Rheology of the artificial sediment mixture*

Twelve artificial sediment mixtures were tested for comparison with the behavior of the 1996 debris flow. Figure 7 shows results gathered with the rheometrical investigation. All the mixtures tended toward a visco-plastic behavior. The Herschel-Bulkley parameter n varied between 0.14 and 0.48. The yield stress ranged from 0.4 to 584 Pa, viscosity from 0.6 to 143 Pa·s. Viscosity increased with the proportion of black marl in the mixture.

Artificial sediment mixtures having the weakest yield stress (AM1, AM2, AM4, AM11, AM12) were all characterized by a low proportion of black marl (< 40%) and/or a high proportion of sandstones (> 50%). In comparison, weathered black marls have a high viscosity. (Malet et al. 2002).

Table 1. Yield stress (τ_c) of the artificial sediment mixtures for 4 solid volume concentrations (ϕ).

ϕ	*LTF*	*AM1*	*AM2*	*AM3*	*AM4*	*AM5*	*AM6*	*AM7*	*AM8*	*AM9*	*AM10*	*AM11*	*AM12*
0.35	1.1	3.4	0.4	44.2	3.5	9.8	15.6	28.5	22.6	7.4	6.9	4.6	4.1
0.40	8.5	10.2	5.9	102.5	6.8	28.9	41.1	72.4	81.6	21.6	20.7	12.8	11.5
0.45	36.4	28.7	12.7	231.6	31.5	61.2	105.7	225.9	220.1	62.5	68.2	49.6	41.7
0.50	87.8	94.6	26.8	524.3	42.6	215.2	201.6	584.2	532.5	284.6	212.3	135.6	118.6

AM1 characteristics (yield stress and viscosity) were close to the 1996 debris flow. However, these results may be skewed. Malet et al. (2002) have shown that natural fluids have a lower yield stress than material *in situ*, even if they have the same grain-size characteristics. We must therefore consider carrying out rheological tests on artificial sediment mixtures which have already undergone flow.

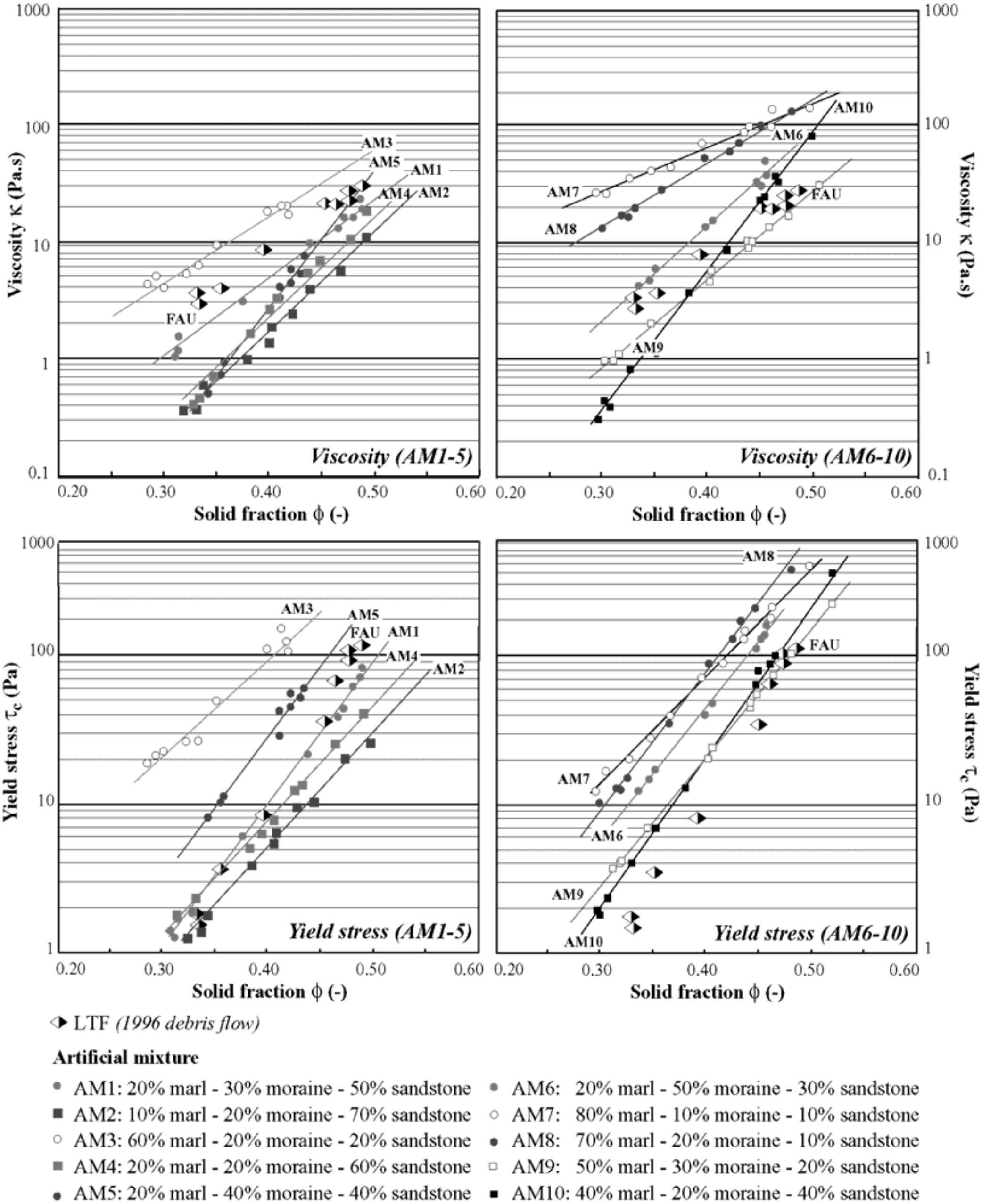

Figure 7. Dynamic viscosity (top of the figure) and yield stress (bottom of the figure) as a function of the total solid volume fraction for ten artificial mixtures and for the 1996 muddy debris flow. Viscosity (κ) has been determined by rheometric tests (parallel-plate). Yield stress (τ_c) has been determined by rheometric tests, slump tests and inclined plane tests.

5 CONCLUSION

A combination of several analyses (geomorphological survey, sedimentological analyses and rheological tests) provides insight on the 1996 debris flow event. Comparison of the 1996 debris flow deposits with the three main 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 brings out the granular character of the flow during the first hectometer and its muddy character beyond that point and as far as the debris fan. Geomorphic observations and laboratory tests show the existence of two source areas: an initiation area and several contributing areas. These contributing areas, characterized by the presence of black marl outcrops and moraines, seem to have supplied the majority of the flow material.

Rheological tests show that the viscosity and the yield stress increase with the proportion of weathered black marl in the mixture and decrease when a higher proportion of sandstone is present. This is in agreement with the grain-size distribution analysis. Nevertheless, additional rheological tests must be carried out on other artificial sediment mixtures to supplement the triangle (Fig. 5) and to define limits in the triangle of the influence of each surficial material. The results of this study provide experimental support for numerical modelling of debris flow runout and spreading; the modelling must take account of scouring phenomena and bulking processes.

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REFERENCES

Arattano, M. 2000. On debris flow front evolution along a torrent. *Physics and Chemistry of the Earth,* Part B, 25 (9): 733-740.

Berti, M., Genevois, R., Simoni, A. & Rosella Tecca, P. 1999. Field observations of a debris flow event in the Dolomites. *Geomorphology* 29 (3-4): 265-274.

Bonnet-Staub, I. 1999. Définition d'une typologie des dépôts de laves torrentielles et identification de critères granulométriques et géotechniques concernant les zones sources. *Bulletin of Engineering Geology and the Environment* 57(4): 359-367.

Costa, J.E. 1984. Physical geomorphology of debris flows. In J.E.Costa & P.J. Fleisher (eds), *Developments and Applications in Geomorphology*: 268-317. Heidelberg: Springer Verlag.

Coussot, P. & Meunier, M. 1996. Recognition, classification and mechanical description of debris flows. *Earth Science Reviews* 40 (3-4): 209-227.

Coussot, P. & Piau, J.-M. 1994. On the behavior of fine mud suspensions. *Rheologica Acta* 33: 175-184.

Fannin, R. & Rollerson, T.P. 1993. Debris flows: some physical characteristics and behavior. *Canadian Geotechnical Journal* 30: 71-81.

Flageollet, J.C., Maquaire, O., Martin, B. & Weber, D. 1999. Landslides and climatic conditions in the Barcelonnette and the Vars basins (southern French Alps, France). *Geomorphology* 30 (1-2): 65-78.

Hübl, J. & Steinwendtner, H. 2000 Estimation of rheological properties of viscous debris flow using a belt conveyor. *Physic and Chemistry of the Earth,* Part B, 25 (9): 751-755.

Hungr, O. 2000. Analysis of debris flow surges using the theory of uniformly progressive flow. *Earth Surface Processes and Landforms* 25 (5): 483-495.

Hungr, O., Morgan, G.C. & Kellerhals, R. 1984. Quantitative analysis of debris torrent hazards for the design of remedial measures. *Canadian Geotechnical Journal* 21: 663-677.

Hungr, O., Evans, S.G., Bovis, M.J. & Hutchinson, J.N. 2001. A review of the classification of landslides of the flow type. *Environmental and Engineering Geoscience* 7 (3): 221-238.

Iverson, R.M. 1997. The physics of debris-flow. *Reviews of Geophysics* 35 (3): 245-296.

Iverson, R.M., Reid, M.E. & Lahusen, R.G. 1997. Debris flow mobilization from landslides. *Earth Planet Science* 25: 85-138.

Iverson, R.M., Vallance J.W. 2001. New views of granular mass flows. *Geology* 29 (2): 115-118.

Jakob, M., Hungr, O. & Thomson, B. 1997. Two debris flows with anomalously high magnitude. In C.L. Chen (ed.), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings 1st International DFHM Conference, San Francisco, CA, USA, August 7-9, 1997*: 382-394. New York: ASCE.

Jakob, M., Anderson, D., Fuller, T., Hungr, O. & Ayotte, D. 2000. An unusually large debris flow at Hummingbird Creek, Mara Lake, British Columbia. *Canadian Geotechnical Journal* 37 (5): 1109-1125.

Johnson, A.M. & Rodine, J.R., 1984. Debris flow. In D. Brundsen & D.B. Prior (eds), *Slope Instability:* 257-361. Wiley: Chichester.

Johnson, K.A. & Sitar, N. 1990. Hydrologic conditions leading to debris flow initiation. *Canadian Geotechnical Journal* 27: 789-801.

Major, J.J. & Pierson, T.C. 1992. Debris flow rheology: experimental analyses of fine-grained slurries. *Water Resources Research* 28 (3): 841-857.

Major, J.J. 1998. Pebble orientation on large, experimental debris flow deposits. *Sedimentary Geology* 117 (3-4): 151-164.

Malet, J.-P., Remaître, A., Ancey, C., Locat, J. Meunier, M. & Maquaire, O. 2002. Caractérisation rhéologique des coulées de débris et des laves torrentielles du bassin marneux de Barcelonnette (Alpes-de-Haute-Provence, France). Premiers résultats. *Rhéologie* 1: 17-25.

Malet, J.P., Remaître, A., Maquaire, O., Ancey, C. & Locat, J. (in press). Flow susceptibility of heterogeneous marly formations: implications for torrent hazard control in the Barcelonnette basin (Alpes-de-Haute-Provence, France). *This volume.*

O'Brien, J.S. & Julien, P.Y. 1988. Laboratory analyses of mudflow properties. *Journal of Hydraulic Engineering* 114 (8): 877-887.

Pérez, F.L. 2001. Matrix granulometry of catastrophic debris flows (December 1999) in central coastal Venezuela. *Catena* 45 (3): 163-183.

Pierson, T.C. 1986. Flow behavior of channelized debris flows, Mount St. Helens, Washington. In A.D. Abrahams (eds), *Hillslope Processes*: 269-296. Allen & Unwin: Boston.

Pierson, T.C. & Costa, J.E. 1987. A rheologic classification of sub-aerial sediment-water flows. In J.E. Costa & G.F. Wieczorek (eds), *Debris Flow, Avalanches: Process, Recognition, and Mitigation*. *Geological Society of America Reviews in Engineering Geology* 7: 1-12. Geological Society of America: Boulder.

Pierson, T.C., Janda, R.J., Thouret, J.C. & Borrero, C.A. 1990. Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and deposition of lahars. *Journal of Volcanology and Geothermal Research* 41: 17-66.

Remaître, A., Maquaire, O. & Pierre, S. 2002. Zones d'initiation et de contribution des laves torrentielles dans les bassins marneux. Exemple du torrent de Faucon (Bassin de Barcelonnette, Alpes-de-Haute-Provence). *Géomorphologie : Relief, Processus, Environnement* 2002 (1): 71-84.

Sivan, O. 2000. *Torrents de l'Ubaye*. Sabença de la Valeia.

Takahashi, T. 1991. *Debris Flows*. IAHR Monograph Series. Balkema: Rotterdam.

Tognacca, C. & Bezzola, G.R. 1997. Debris flow initiation by channel-bed failure. In C.L. Chen (ed.), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings 1st International DFHM Conference, San Francisco, CA, USA, August 7-9, 1997*: 44-53. New York: ASCE.

Vandine, D.F. & Bovis, M. 2002. History and goals of Canadian debris flow research, a review. *Natural Hazards* 26: 69-82.

Wieczorek, G.F., Mandrone, G. & DeCola, L. 1997. Influence of hillslope shape on debris flow initiation. In C.L. Chen (ed.), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings 1st International DFHM Conference, San Francisco, CA, USA, August 7-9, 1997*: 21-31. New York: ASCE.