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Classification of debris-flow deposits for hazard assessment in alpine areas

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ABSTRACT: The choice of the relevant mechanical characteristics of debris flow is an important issue in hazard mitigation. Many scientists agree that the behavior of debris flow can be classified into different families. For this purpose the applicability of Ancey's (1999) classification was tested with field investigations. This rheophysically-based classification allows one to link debris flow deposit (geomorphological) features to mechanical properties. The study uses all the information (deposit shape, qualitative shape of flow curve, grain size distribution) coming from a comprehensive field survey to estimate the applicability of the method. This information is recorded on debris flow levees (mainly cross-section, stability of the deposit, dry cohesion) since they are the most common traces in the surveyed area. In addition, exploratory rheological tests were performed with a parallel-plate geometry. These measurements show a good qualitative agreement between rheophysical characteristics and geomorphological features. Some problems still need to be solved before using numerical values given by rheological tests, but the classification can already be used to guide the engineer in choosing the right constitutive laws for modeling.

1 INTRODUCTION

The main goal of this study is to give a methodology for discriminating between different rheological behaviors of alpine debris flows. An extended field survey was carried out on several watersheds subject to debris flows in Canton Wallis (Southern Switzerland). In these watersheds, debris flow traces and characteristics (levee cross section, lobe shape, stability of the deposit, dry cohesion) are differentiated according to a classification based on a mechanical differentiation of flow indicated by a rheophysical approach. Since it was not possible to associate every trace to a defined flow type (mainly levee cross-section were used in this study), a more efficient method for differentiate between traces was sought. In order to determine which kind of mechanical behavior could be derived from a levee cross-section, rheometric experiments were performed. These experiments show a good agreement between flow-type identified in the field and the measured one and thus justify the use of the rheological approach for detailed watershed analysis.

It is not until now that theoretical studies on the differences in the rheological behavior of debris flows have been conducted. For the moment there is no broad agreement on a classification of debris flows. Starting from a purely rheophysical viewpoint, Ancey (1999) proposes a division into three classes (viscous, viscoplastic and frictional behaviors) and attempts to link rheological properties and geomorphological characteristics. He distinguishes three types of debris flow: muddy, granular, and fluid debris flows. Cannon (2000) observed two debris-flow types in California based on their geomorphological characteristics. Takahashi (2000) differentiated debris flow on the basis of the ratio between diverse components of the total shear strength (*i.e.* the Bagnold and Reynold numbers). This led him to distinguish four debris-flow types: granular, viscous, muddy, and hybrid.

The existence of different types of debris flows is well observed in the Walliser Alps, an area with a wide range of geological characteristics. Field observations show that each class, according to Ancey's classification, can be correlated with parameters like stopping slope, deposit shapes and aspect, and grain size distribution. Furthermore these classes seem to be related to different constitutive laws. The classification used here makes it possible to link field observations and flow mechanics. This is of great importance now that commercial modeling programs are available. Many of these models are based on a specific flow law. Therefore the classification presented here may provide guidance for engineers when choosing an appropriate model.

2 MECHANICAL CLASSIFICATION

The classification given by Ancey (1999) was chosen because of a broad applicability to the field (see Table 1). Concepts underlying this classification mainly come from rheophysical analysis and are based on previous works done by Coussot (1997) and Ancey (1997). The mechanical behaviors proposed in Table 1 are derived from the different flow regimes observed on artificial suspensions of glass beads and colloidal particles (mainly kaolinite). The different flow regimes are identified on a diagram connecting shear rate-solid concentration (see Fig. 1), where limits between regimes are correlated with a series of major dimensionless numbers such as the Péclet number, Bagnold number, Reynolds number, etc. (for more details, see Coussot and Ancey 1999).

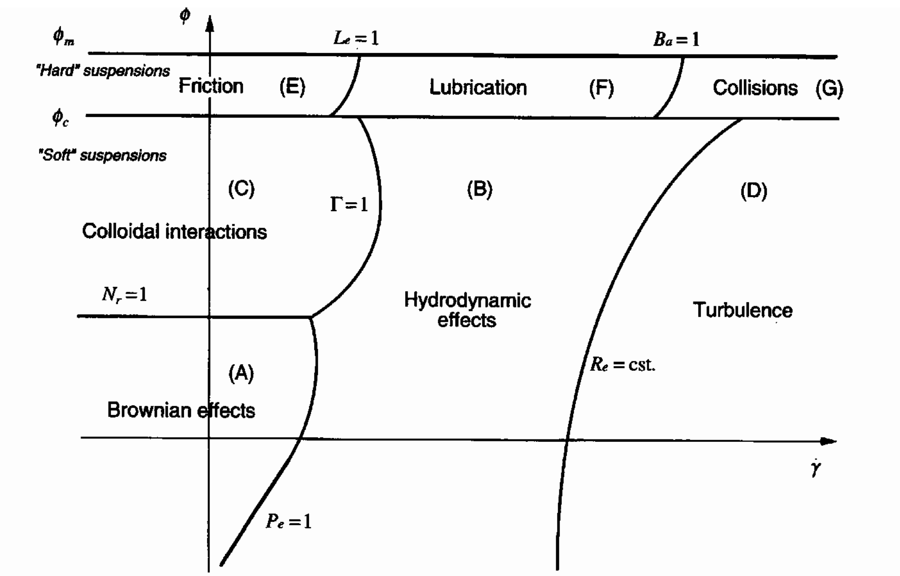
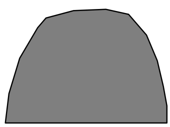
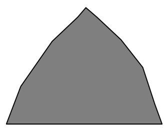


Figure 1. Simplified diagram of flow regimes, where Pe = Péclet number, Nr = repulsion number, Γ = a ratio between viscous and colloidal interactions, Re = Reynolds number, Le = Leigthon number, Ba = Bagnold number, ϕ_m = the maximum random solid concentration and ϕ_c = the minimum concentration for a network of particles in close contact to form (for more details see Coussot & Ancey 1999).

This rheophysical approach differs from other approaches in particular from the classical continuum medium approach (*e.g.* Hutter et al. 1996) or phenomenological continuum medium approach (Iverson 1997). In the first one stress and deformation are analyzed in accordance with the principles of mechanics (material indifference, independence of the referential, etc.) and with thermodynamics (conservation of the energy). Physical explanations for causes of deformation are not given. The second approach uses a generalized experimental law to describe the movement at a macroscale level. This description does not try to explain the change of media microstructure.

The rheophysical approach presented here aims at explaining the microstructural changes. This theory scales-up microscale movements to describe the movement at the macroscale level (Evesque 2000). This approach is complementary to the phenomenological one and has the advantage of permitting a linkage between field material characteristics and theoretical model. It is assumed that the matrix has a great influence on the debris flow mechanical behavior and that information shown in Table 1 (mainly following levee cross-section shape) is representative of the debris-flow body. The consideration of the front effect, generally of a more granular appearance, is not possible. Based on these considerations and preliminary field surveys a debris flow classification into three different types can be given (Ancey 1999).

Table 1. A rheophysical classification of debris flows (adapted from Ancey 1999).

Mechanics	**Scientific name**	viscoplastic	collisional-frictional	frictional-viscous
Mechanics	**Appropriate rheophysical model**	Herschel-Bulkley Bingham	Coulomb-like, collisional-frictional constitutive equation	Coulomb-like at low speed Newton-like (or power-law) at high speed
Field observation	**Common name**	muddy	granular	fluid
Field observation	**Deposit appearance**	smooth with clear limits in the field, very cohesive once dry  levee cross-section	rough with no clear deposits limits in the field, non cohesive once dry  levee cross-section	terrace-like deposit, very cohesive once dry  whole body cross-section (not the same scale as levee cross-section sketch)
Field observation	**Stopping slope**	< 2°	< 10°	< 1°
Field observation	**Grain size**	grains + + matrix + + clays +	grains + + matrix- clays - -	grains - / + matrix + + silts + clays -

The following notation is adopted :

– – very little content
– little content
\+ high content
\+ + very high content

Table 1 is divided into two main parts. The first two rows are related to the mechanics. The last four rows are dedicated to the corresponding field characteristics. In the Alps, the valley setting means that debris flow deposits are rarely observed and the more current traces are levees. Therefore, levee cross-sections are included in Table 1. However, the deposit descriptions given in the row "deposit appearance" are also valid to describe deposits where snout, body and levees are present.

A remark is essential in order to avoid any confusion. The name muddy debris flow is used according to this classification. It covers a range of mechanical behaviors whereas other classifications speak of granular debris flow. To avoid this linguistic inconsistency it is proposed to use the scientific name viscoplastic or to speak of debris flows with a muddy behavior (in opposition with the muddy appearance).

3 FIELD SURVEY

The field survey was performed in Canton Wallis, Southern Switzerland. This part of the central European Alps has a complex geology (Trümpy 1980), which avoids possible bias in sediment transport mechanisms due to lithological effects (see Fig. 2).

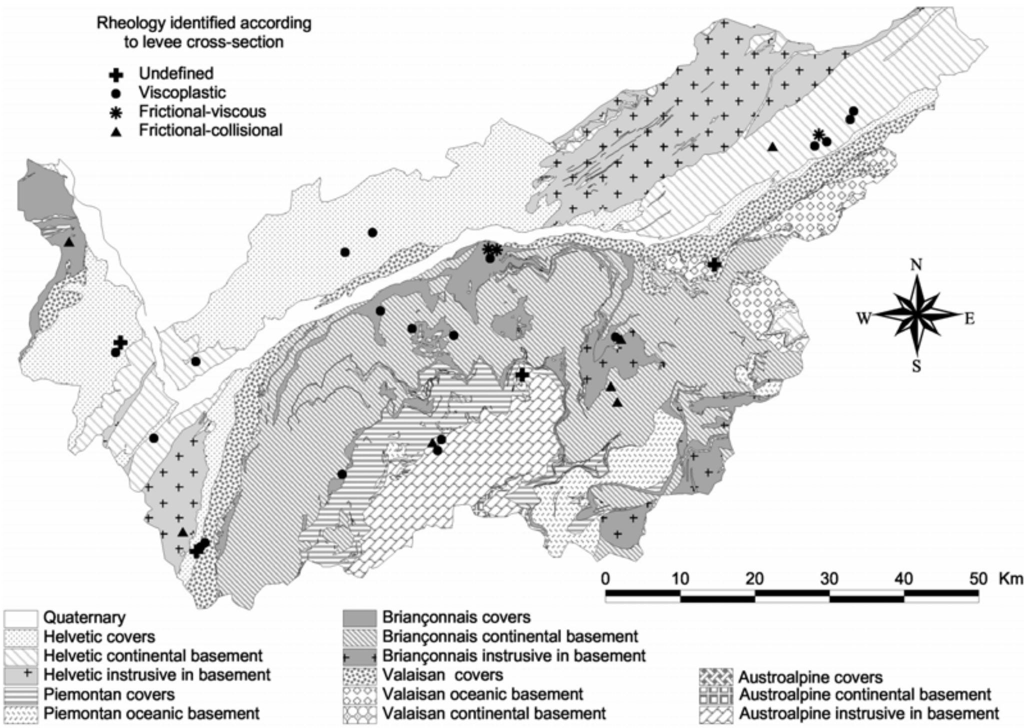


Figure 2. Spatial distribution of the surveyed levee cross-sections compared to the paleogeographic domains encountered in Canton Wallis (lithology from Steck et al. 1999).

For the 35 observed watersheds, levee cross-sections were inspected and compared to the guidelines shown in Table 1. Some of the levees could not be attributed to one type of mechanical behavior (bold cross in Figure 2). The first result of the survey is that the three debris flow types are present on the study area.

Thirty-one observed cross-sections could be attributed to an identified flow-type: viscoplastic (*i.e.* muddy), the collisional-frictional (*i.e.* granular) and the frictional-viscous (*i.e.* fluid) behavior. However four deposits could not be attributed to one of these flow-types and are reported as undefined. Figure 3 summarizes the results of the field survey. It underlines two points of great importance:

- Four traces, that is 11 % of the whole sample, are undetermined. The presented classification is not sufficient in these cases to allow the engineer to choose the most appropriate flow type.
- In this part of European Alps viscoplastic debris flows are the most common type (60 %).

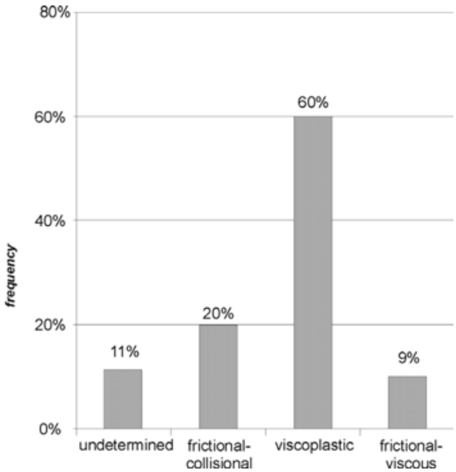


Figure 3. Rheological behavior determined in the field.

4 RHEOMETRY

As stated in the previous section, not all levee cross-sections could be characterized as a particular debris flow type according to Ancey's (1999) classification. To improve our capacity to determine a specific flow type, preliminary rheometric tests were performed on samples collected from debris flow deposits at the field sites. Since only small grain size can be used, it will be assumed that the rheological behavior of the entire debris flow mass is mainly governed by the fine particles.

The rheometer used here is a device that allows one to shear a small sample of debris flow matrix between a fixed plate and a rotating one (see Fig. 4). Indeed with a parallel-plate geometry and the tested kind of suspension, it is possible to ensure an homogenous filling of the paste in the testing tool. When using a coaxial-cylinder geometry, this is not possible. However the parallel plate geometry presents a major drawback: a non-uniform shear stress along the radius. This could be avoided if the rotational tool had a cone shape. But, in the case of a cone-plate geometry, grain shrinkage becomes a major limitation of the measurement. Another advantage of the parallel-plate geometry is the ability to observe dysfunctions (such as boundary slip, rupture of the sample, loss of material to the edge) and the possibility to create rough boundaries at a reasonable cost.

In this study, tests are strain-controlled in order to obtain a flow curve (Barnes et al. 1997). The plate-plate geometry allows the testing of highly concentrated suspensions of water and mineral particles, the diameter of which is as large as 400 µm. With this particle size the annulus (*i.e.* the space left between the fixed plate and the rotating one) is set to 2.8 mm (see Fig. 4). Once the specimen is placed between the two plates, a small strain rate is applied first. After 10 seconds increments in strain can be applied (allowed by the material reaction) until a strain-rate of 70 s^{-1} is obtained. Then the same strain-rate path is followed inversely to reach 0 s^{-1} (see Fig. 5). The normal testing procedure includes 4 to 6 shear experiments for the same material with different water contents.

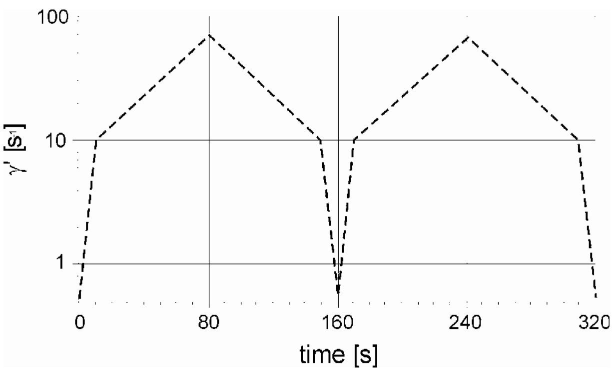


Figure 4. The rheometer used in this study, note the 2.8 mm gap between both plates.

Figure 5. Rotating conditions procedure during the rheometric tests.

To prepare the material for testing, 7 kg of sediments up to 20 mm were collected from debris flow deposits. This quantity is necessary to obtain sufficient material for rheometer tests, especially for the material coming from collisional-frictional deposits. The samples were always taken away from the levee inside mass to avoid bias due to dewatering after the stop of debris flow or due to post-event rainfall erosion. Then the material is wet sieved. After drying, 20 % by weight of water is added again to the obtained mineral powders. The formed suspension is vigorously mixed for 30 minutes.

5 RESULTS

The comparison between the rheological behavior identified in the field and the behavior measured on a rheometer shows a very good agreement (see Table 2). Moreover all undefined traces from the field survey could be attributed to a determined debris flow type. In the field, the doubt was always between viscoplastic and collisional-frictional types. So it is not very surprising to see that all these traces are attributed to one type only. However if more samples had been tested it is probable that some undefined traces would have been attributed to collisional-frictional type. The qualitative response of the rheometer is very well marked (see Fig. 6); it could explain the very good correspondence between identified and measured behaviors.

Table 2. Results of the comparison between rheological behaviors identified on deposit samples and those measured on a rheometer.

		measured as		
		viscoplastic	collisional-frictional	frictional-viscous
identified as	viscoplastic	21	-	-
	collisional-frictional	-	7	-
	frictional-viscous	-	-	3
	undefined	4	-	-

Direct results of rheometry tests are presented in Figure 6 under flow curve format (shear stress vs. shear rate). As seen in this diagram there are differences between theoretical and experimental curves. Theoretical curves are determined on an artificial suspension of a well defined material (Ancey 1999). Experimental curves shown in the lower part of Figure 6 are typical curves obtained from tests run on samples of viscoplastic, collisional-frictional and frictional-viscous materials. All tests give the same qualitative response as that shown in Figure 6. Even if a sensible difference is observed in some cases between theoretical and experimental curves, rheometer test data are sufficiently reproducible to be used as a guide for the choice of the rheological behavior.

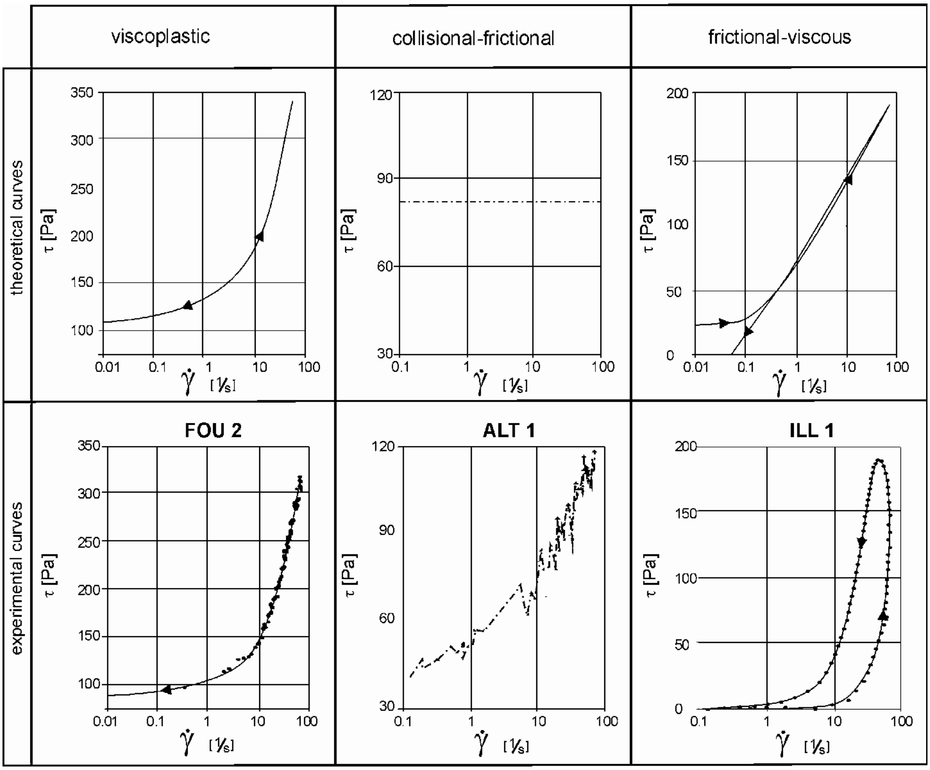


Figure 6. Comparison between theoretical curve and experimental rheograms obtained for some representative watersheds.

The differences found between theoretical and experimental curves are in part due to the natural complexity and in part due to rheometer limitations.

For collisional-frictional samples, it seems that the matrix has a behavior located between the viscoplastic theoretical curve and collisional-frictional theoretical curve. This is probably due to the composition of this matrix containing some colloid particles that are able to put into suspension the coarsest particles that have settled at low strain-rate. The erratic behavior is due to the induction of normal stress in the measuring plate of the rheometer (*i.e.* the rotating one) following the rolling of coarse particles on each other. This process is audible during shear test by squealing between grains.

For frictional-viscous samples, the negative hysteresis (and not negative thyxotropy because it is not clear if the material could recover its former properties after shearing) is due to the temporal evolution of the sample during the test. Observation of both a clay and a bleeding layer after the test indicates that a segregation appears during the shear. Figure 7 clearly shows the loss of medium size grains after shear. This leads to the conclusion that the energy provided by shearing is sufficient to break some clay aggregates. Only preliminary results take into account these effects of granular material for cement suspension (Catalot-Martinent 1997, for debris flows, Bardou 2002).

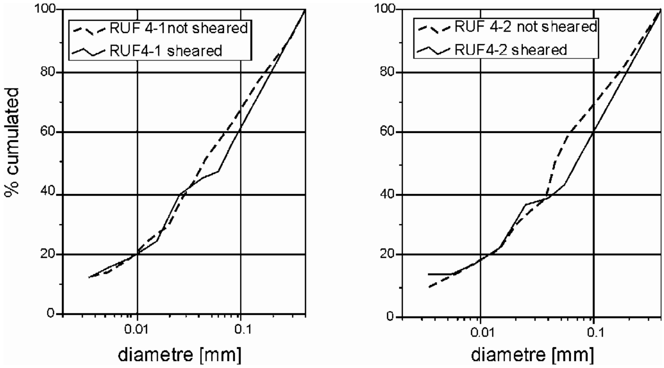


Figure 7. Grading curves for 2 samples of material with frictional-viscous behavior.

6 DISCUSSION

Although quantitative results are not yet significant for the moment, apart from what refers to the viscoplastic behavior, the qualitative response is repeatable. Therefore the use of rheometry constitutes a good complement to gather field characteristics used in Ancey's (1999) classification. Moreover, additional surveys conducted on more than 20 other watersheds (not presented here) show that in Canton Wallis no other flow type is found. For a major part of the inspected levees the choice of debris flow type could be done without going trough these complex rheometric tests.

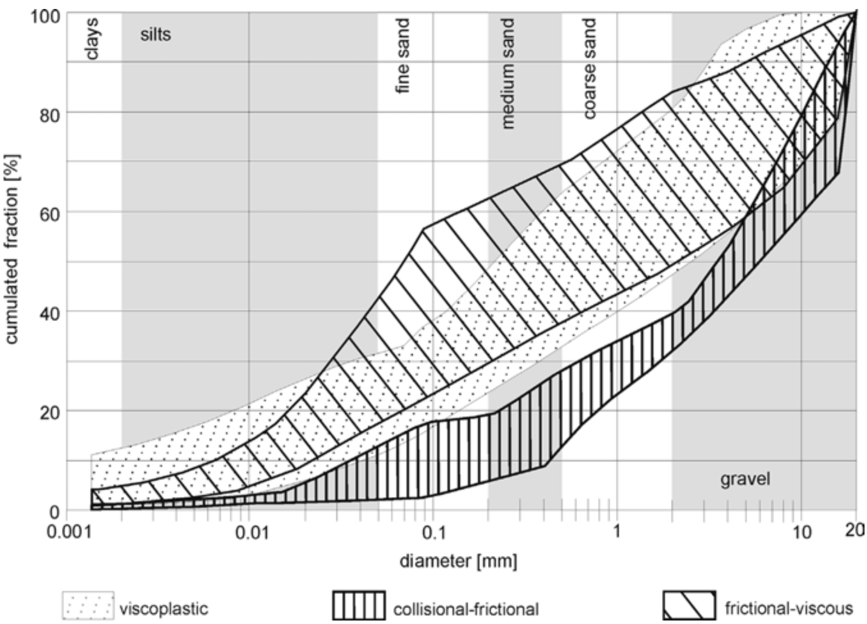


Figure 8. Envelope of grading curves of every samples of debris flow deposits, plotted with indication of their mechanical behavior.

Another point, which can be highlighted from these data, is that the debris flow type is not linked to the watershed. For instance, three watersheds show that it is possible to observe two behavior types at the same location. Careful field observations and bibliographical analyses (if possible) are then necessary to avoid a wrong choice in constitutive laws of the chosen model. This multiple behavior shows the importance of the material characteristics on the debris flow type. For instance, the grain size distribution can be related to the debris flow type. Envelope curves shown in Figure 8 indicate a clear separation of the grading curves related to viscoplastic and collisional-frictional material. If the envelopes of viscoplastic and frictional-viscous debris flow overlap, their shapes are sufficiently different to highlight the importance of this characteristic on the mechanical behavior (peak of silts in frictional-viscous material). This difference in composition seems to speak in favor of the chosen classification.

The effect of these composition changes (effect of colloidal particles vs. grains, type of colloidal particles) is not yet well understood. Some works have been done to correlate other material characteristics (*e.g.* geology, mineralogy) with debris flow behavior (Cannon 2000, Bardou et al. 2003), but general recommendations cannot be given at this stage.

Thus if no field data are available, it is recommended that engineers identify triggering zones and test samples from these areas with a rheometer. The identification of triggering zones should be based on the susceptibility of each part of the watershed and on the possible triggering mechanisms (channel erosion initiated or landslide initiated debris flow). As far as we know, only two watersheds have been analyzed within prediction studies. On these watersheds where no levees were available, rheometer tests were performed on material from the triggering zone. The results of these tests did not follow the hypotheses based only on material appearance (based on the criterion given in Table 1). By chance, soon after these measurements, debris flows occurred and the levees could be inspected. In both cases the result of measurements were confirmed by the field determination (case S^{t}-Antoine torrent in France, Ancey unpublished technical report, or Vésivi torrent in Switzerland, Bardou unpublished technical report).

It is finally useful to recall that viscoplastic debris flows, which are often called a muddy debris flows, does not always have the same constitutive law as debris flows described as muddy based on their appearance during flow. A debris flow with a granular appearance (i.e. frictional-collisonal) could be of a muddy behavior mechanically speaking.

7 CONCLUSIONS

Ancey's (1999) classification has been applied in the field, resulting in good agreement with independent rheometric analysis. The classification seems to be exhaustive since the field survey reveals no other identified debris flow type. The indetermination encountered in the field can be solved by the use of rheometric tests performed on sampled debris flow deposit materials. The link between rheophysical properties and geomorphological shapes is supported by the good agreement as shown in Table 2. The exhaustiveness on the surveyed area and the physical base of this research leads to the hypothesis that this classification could be similarly applied elsewhere.

Morevover, rheometric tests provide good qualitative results. Debris flow types are well discriminated on this basis, even those that are not attributed to a class by field survey. This is a valuable tool for the engineering practice. Quantitative results cannot be used for the moment apart from those related to the viscoplastic behavior. Operational use of numerical values provided by the rheometric tests pass trough an improvement of the measuring devices and the understanding of the material property implication in the physics of the movement.

However it has to be kept in mind that different debris flow types may occur on the same watershed. The use of scenarios (*i.e.* choice of set of parameters), incorporating different debris flow types, are a mandatory point when conducting hazard zoning related to a magnitude/frequency analysis. Case studies (from private consultants) based on this classification show that it is a valuable help in order to prepare hazard zoning. Among other indices (*e.g.* historical events) the identification in this rheological classification helps to determine the flow mechanics for debris flows, especially in torrents, where two kinds of debris flows may occur. Moreover, when a debris flow type is identified as viscoplastic, the formulas developed by Coussot (1997) can be used to assess the endangered areas.

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