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The 3D Structure of the Super-Sauze Earthflow: A First Stage Towards Modelling its Behaviour

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Abstract. In the "Terres-Noires" of the Barcelonnette basin, France, the Super-Sauze earthflow is being studied to understand the mechanisms of triggering, slidding and flowing and to propose a predicting dynamic behaviour model. This paper describes the main results of an on-site geotechnical investigation carried out in 1996, which allowed us to establish precisely the internal 3-D structure of the moving mass (position and shape of the paleotopography, functioning of two flow units from the surface to the depth and spatial subdivision of the flow into compartments using contrasts of velocity, by morphological aspects, or mechanical and hydrodynamical characteristics of the material). Moreover, studies of old aerial photographs identified the importance of the buried topography on the dynamic evolution of the flow.

1. Introduction.

The callovo-oxfordian " Terres-Noires " of the Barcelonnette basin (Alpes-de-Haute-Provence, France) are known for their susceptibility to weathering and erosion (Antoine et al., 1995). Several earthflow are active and affect all or parts of basins. The studiedearthflow affects the north-facing slope of the Brec Second crest in the " Roubine " area, a 75 ha stretch of bad-land cut in black marls (Flageollet et al., 1996a). The combination of steep slopes (up to 35°), downslope stratigraphic dip and absence of vegetation makes this basin one of the most landslide, flow and debris-flow prone areas in the Ubaye valley. The Super-Sauze earthflow has been under study since 1991 because of its entirely natural evolution, with the aim to understand the apparent easy transformation of slide into flow and the eventual generation of a rainfall or snowmelt-induced debris-flow.

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2. Geomorphological features.

The Super-Sauze earthflow (Fig.1) has a characteristic morphology of blocks and panels of marls that break away from the main scarp (2105 m) by plane ruptures, accumulate and progressively deform and result in a heterogeneous debris-flow. Uphill, the main scarp, inclined at approximately 70°, cuts into morainal deposits (about ten meters thick) and subjacent *in-situ* black marls steep slopes about 100 m high. Immediately below the main scarp, the so-called " upper-shelf " appears as a block field, with black marls panels and dihedrons more or less buried in a very heterogeneous formation. The reworked material then transforms into a flow over a distance of almost 500 m. Progressing downstream, an area of dislocated and disintegrating blocks passes to an uneven, rough, surface of crumbling blocks and finally to a slightly uneven surface scattered with calcite and moraine pebbles, weathered stones and flakes of various sizes. The intermediate slopes on this section range up 20 to 25°. The relatively rectilinear profile is interrupted downstream by the slight convexity of the " lower shelf ". The toe of the moving mass is presently at an altitude of 1740 m ; the flow has progressed over a distance of 800 m since it started in the 1960's.

Surface drainage operates in small gullies, rills and an axial main intra-flowing gully with an intermittent run-off, and in two lateral gullies, each incised into *in-situ* marls on one side and into the debris-flow in the other side, with perennial run-off. Flow varies greatly with the season and the pluviometric conditions (Velcin, 1997). Their role is significant in drainage and particularly in erosive action. The axial, intra-flowing gully and the western gully transport an appreciable solid load, with two consequences : the first in terms of balancing incoming and outgoing material, the second in terms of maintaining the instability.

The *in-situ* marls reinforce the main scarp and the flanks of lateral gullies, and also crop out at three places in the accumulation zone (Flageollet et al., 1996b). The marl is a compact formation with facies of black clay shale. The spelling cuts the massif into small beds, flakes or irregular slabs. Fracture planes and sedimentary structures outlined by beds of calcite can also be observed along the lateral gullies. Covering the in-situ marls in the debris-flow, disintegrating slabs and blocks of marls vary in size (from a few cubic meters to several tens of meters). With distance downslope these sharply ridged blocks of marl turn into weathered, round and smooth fragments. These fragments fine downstream and are mixed in a heterogeneous marl-clay formation. This latter formation is composed of a matrix of fairly fine clay containing pebbles and crumbly flakes. In the wettest zone of the flow, this formation can become a very liquid mud.

3. General objective.

The landslide morphology indicates even, before any closer investigation, that the moving mass covers a more or less intact paleotopography of roughly parallel crests and gullies. Depending on position and direction, this paleotography must have a significant effect on the thickness of the flow, depending on its location over a gully or a crest, fully -or partly- filled, and also on water pathways.

In addition to the reconstruction of this paleotopography, modelling the evolution of this flow needs also to estimate the velocity and the volume of debris mobilized by the flow.

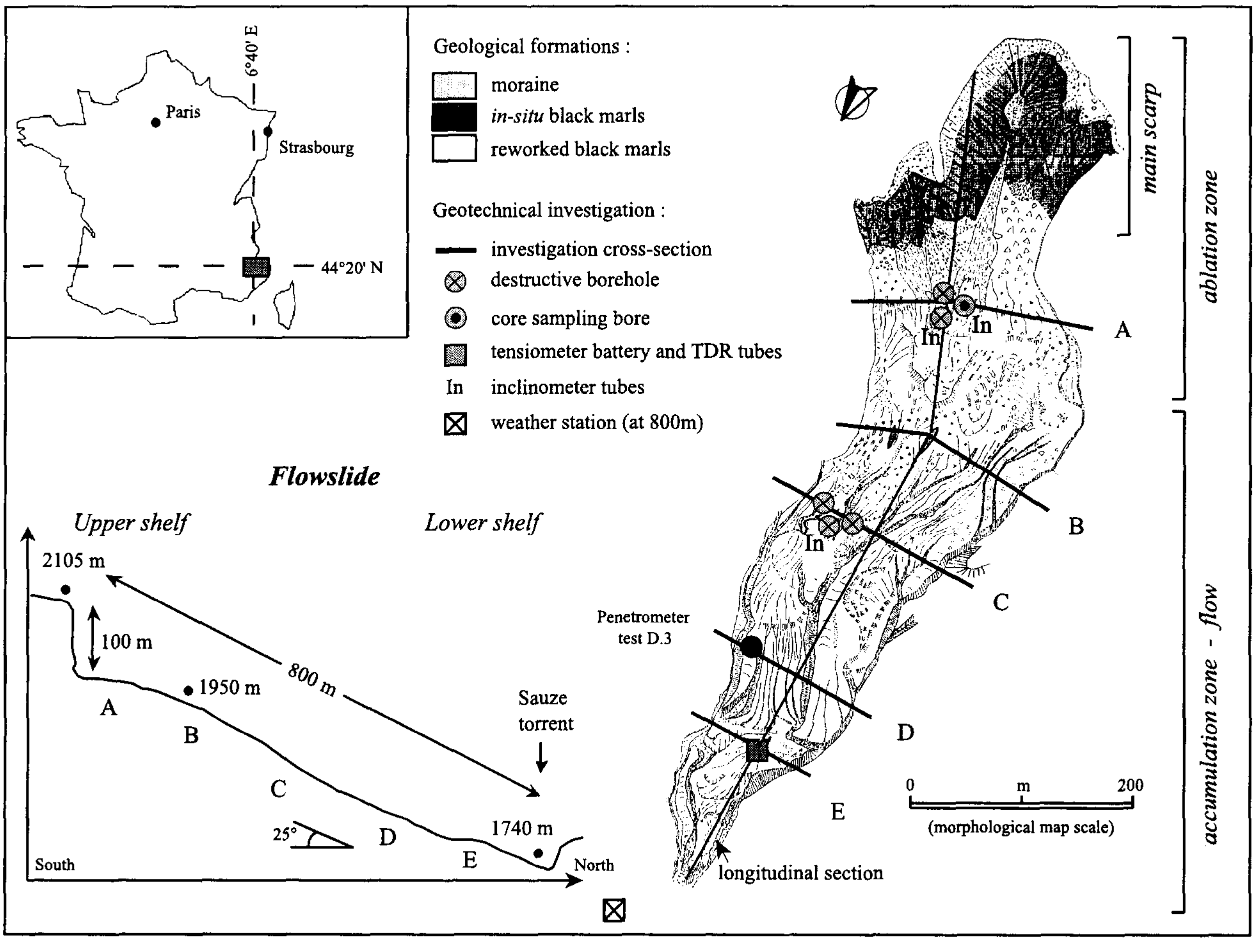

Fig. 1. Geographic setting of the earthflow and of the investigation cross-sections.

Thus, to assist in the choice of behaviour models, our initial on-site investigation examines :

- the paleotopography (i.e. shape, position, depth) of the gullies buried under the moving material and the limit, in depth, of the active movement (internal slip surface or zone of transition) ;
- the mechanical and hydrodynamical characteristics of the flowing material (i.e. resistance to shearing, pressiometric modulus, viscosity, permeability) ;
- the influence of the paleotopography on the behaviour of the earthflow (i.e. velocity, preferential flow paths).

4. Geotechnical investigation.

4.1. Methods.

We conducted a geotechnical investigation in summer and autumn '96. Because of the difficult accessibility (wet and muddy zones, large and deep gullies), " light " investigative tools were chosen (dynamic penetrometer tests, percussion drilling) supplemented by " heavier " tools (core sampling bore, destructive drilling), to install inclinometer tubes and open piezometers, and to carry out pressiometric and permeability tests. The general principle was to correlate the results obtained by these various tools at several points, and then to extend the investigation to five cross-sections (A, B, C, D and E) using the more handy tools such as the dynamic penetrometer (more than one hundred tests) and the percussion drilling (twenty borings). Cross-sections are situated near the topometric survey sections (Fig. 1).

4.2. Interpretation of the penetrometer tests.

The low weight of this equipment (a mere 200 kg !) enabled us to use it in areas inaccessible by the others tools. The machinery limited our investigations to depths of less than 10 m, mainly because of lateral rubbing that developed when passing through unstable layers.

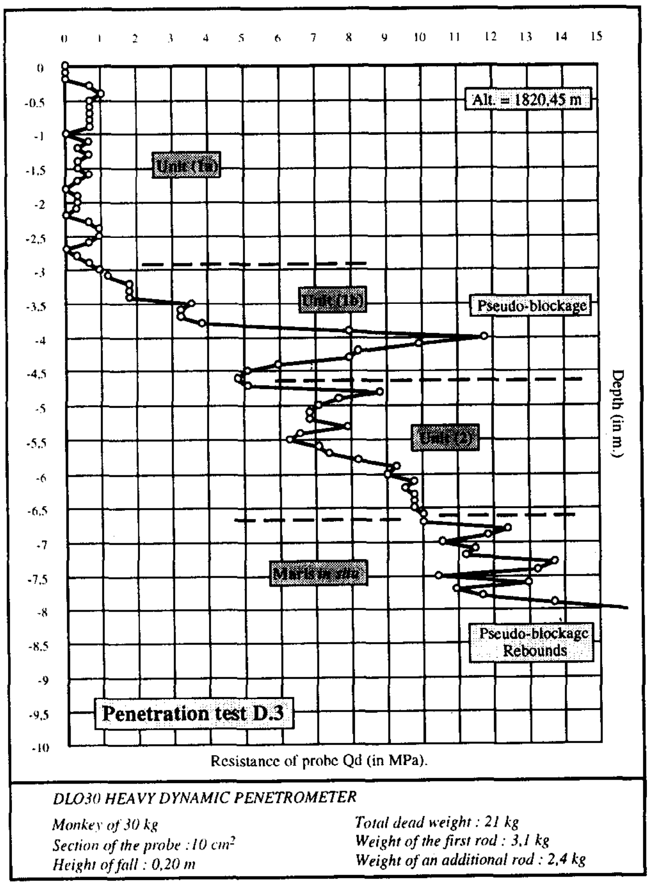

Fig. 2. Penetrometric curve D.3.

Similarly, the presence of numerous blocks of moraine or of fairly solid panels of marls was a major inconvenience as the probe couldn't penetrate this very resistant material. Moreover, when stones or pebbles were buried in a less resistant mass, the probe couldn't push them (creating a succession of localised peaks in the penetrometric curves). In the *in-situ* marls (or in a block of marl buried in the flow) the resistance increases progressively, reaching values of 25 Mpa or more where paleotopography is reached. Sometimes, we were able to drill through a thin resistant layer by forcing the drive, and then to continue drilling through a less resistant layer. The penetration test D3 (Fig. 2) clearly illustrates this major problem of " pseudo-blockage ", which could have been partly solved by using a more powerful machinery. Penetrometer tests should be used very carefully in stable saturated soils and in fine submerged soils (French norme NFP 94-115, 1996).

Because interpretation of the test results can be difficult due to " blind " testing, several gaugings were carried out with pressiometric trials, and disrupted samples were taken for laboratory analysis.

In most of the penetration tests, in accordance with resistance variation criteria (rupture in the curves, transition), three layers were identified in the flow. Thus, the geotechnical investigation allowed us to define, with good precision, the position and shape of the paleotopography and to identify an internal slip surface in the reworked material.

5. Primary geomorphological and geomechanical results.

5.1. Position and shape of the paleotopography.

To reconstruct the position and shape of the paleotopography, we used both information obtained by the on-site investigation and by photo-interpretation of 1956' and 1995' aerial ortho-rectified photographs (Weber et Bolley, 1998). The buried topography is made of a series of crests, almost intact in the accumulation zone, and three *in-situ* crests emerge more or less permanently from the flow near the B profile (Fig. 3a).

The flow is thickest in the axis of the buried main gully of the 56' torrential basin. It reaches :

- a maximum of 20 m in the ablation zone (A cross-section), using the destructive drilling ;
- a maximum of 8 m on the B cross-section (Fig. 3a) ;
- approximately 20 m in the eastern part of the C cross-section, which corresponds to the confluence of the 56' torrential basin gullies (Fig. 3b).

Then it decreases progressively downstream (8 to 9 m on the E cross-section, a few meters at the toe).

The uncertainty in thickness is smallest for profiles B to E. The position of the substratum in the ablation zone is still uncertain, due to the numerous pseudo-blockages in the upper-part of the A profile. This arises partly because of the presence of morainal blocks or of cohesive marl panels in this area. Downstream, penetration was easier, partly because there are fewer morainal blocks and partly because of lower cohesion of the marl blocks in the reworked formation (Flageollet et al., 1996b). The collapse (plane ruptures ?) of the upper part of previous *in-situ* crests over

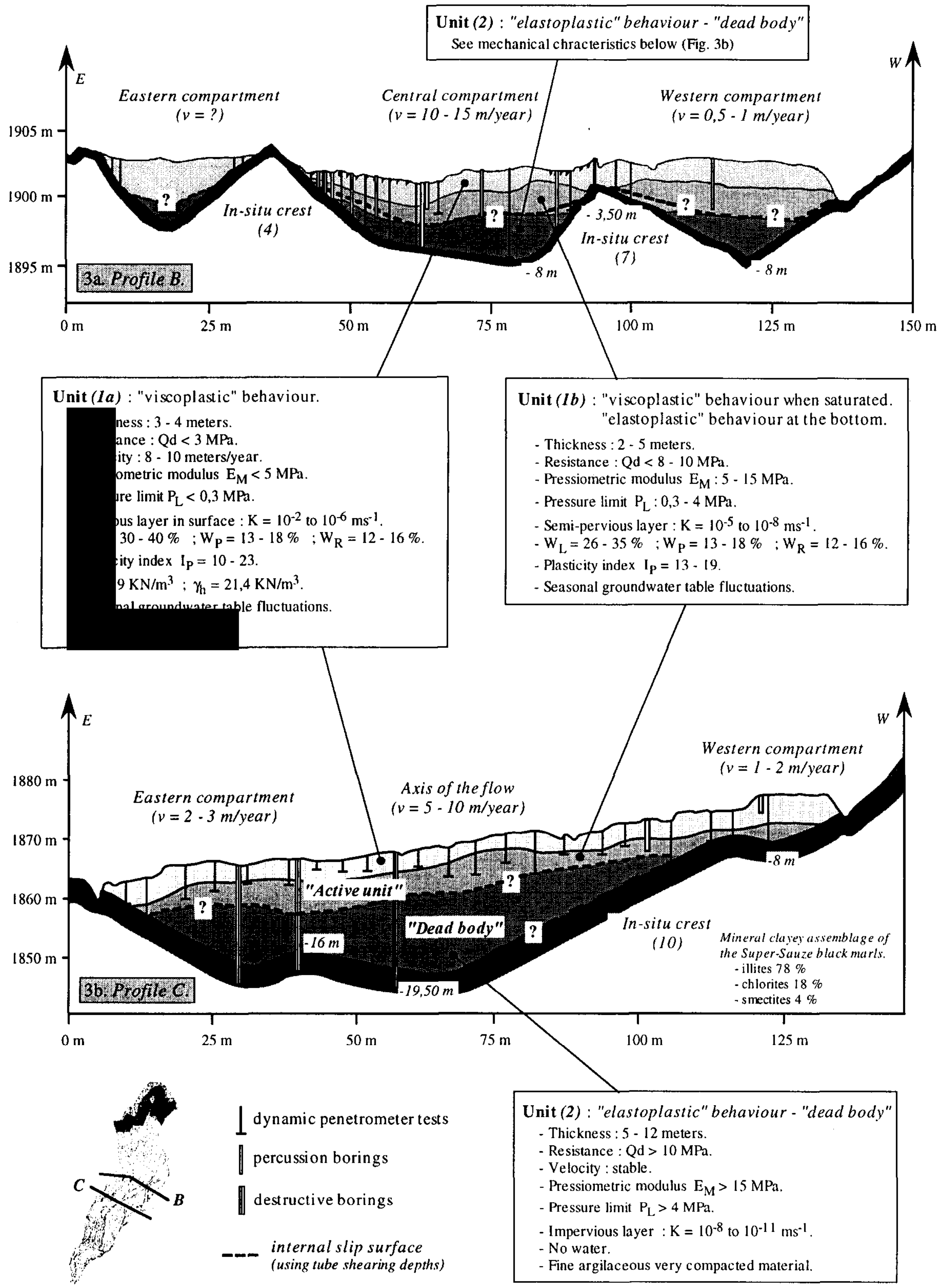

Fig. 3. Internal structure, mechanical and hydrodynamical characteristics of the flow (3a. B cross-section , 3b. C cross-section). (Genet et Malet, 1997, Herrmann, 1997, Klotz, 1998).

an elevation of 80 m created the main scarp. However, a question is raised : does the lower part of these crests still exist under the upper shelf (A profile) ? This has to be answered to distinguish the actual transition between

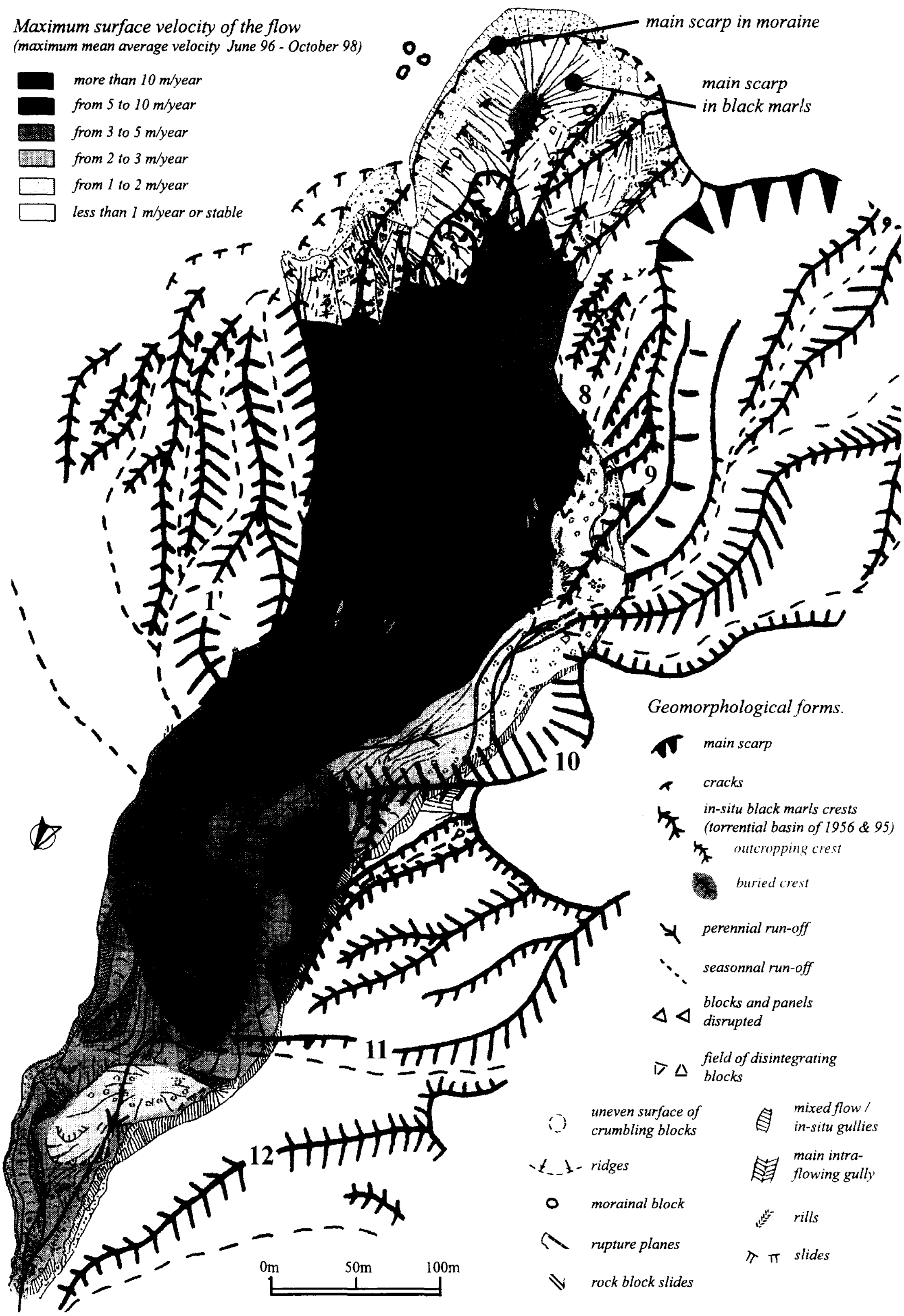

Fig. 4. Influence of the 1956 buried paleotopography on the behaviour and surface velocity of the flow.

ablation and accumulation zones.

5.2. Geomechanical and hydrodynamical characteristics of the flowing material.

Three " geotechnical " layers can be indentified in the flow, based upon resistance criteria, contrasts in the nature of the soil and shearing of the inclinometric and piezometric tubes. The vertical structure of the flow is composed of (Genet et Malet, 1997) :

- a surficial unit 5 to 9 m thick (Qd < 10 MPa, E_M < 15 MPa, surface velocity greater than 5 m/year). A potential internal slip surface has been identified at about 5 m depth on the B profile and 8 to 9 m depth on the C profile. This corresponds more or less to the limit between the unit *(1b)* and *(2)* on the penetrometric curves. According to the shape of the paleotopography and to the seasonal position of the groundwater table, this active unit can be subdivided in two sub-units (named respectively *(1a)* and *(1b)* on the penetrometric curves).
- a deeper unit with a maximum thickness of 10 m on the C profile and 5-6 m on the B profile, with unknown internal characteristics. Based on the inclinometric measurements and the pressiometric trials (E_M > 15 Mpa, Pl > 4 Mpa), we infer this is highly compacted and either a stable " dead body " or a very slow moving material, as identified on the La Valette landslide (Colas, and Locat, 1993) or on the Slumgullion earthflow (Varnes, and Savage, 1996).

Thus the accumulation zone is composed of two units, the upper unit is a very active and very wet viscous mud formation (semi-pervious material with groundwater fluctuations between -0.5 to -1.5 m, noticeable influence of tension cracks on groundwater recharge), whereas lower unit is a stiff compact rigid/plastic and stable formation (impervious material and dry conditions).

We also noticed a " deterioration gradient " of the marl blocks from the surface to the depth. Unit *(1a)* contains a few small blocks of marl in an advanced stage of deterioration, whereas unit *(1b)* contains more stable but deteriorating blocks. This explain why unit *(1a)*, with a very fine damp matrix, can turn in a liquid mud in the wettest zones of the flow, especially during snowmelt, typically from April to June (Genet, and Malet, 1997).

5.3. Behaviour of the flow.

As noted above, the material flows preferentially following the axis of the old and buried gullies. This is particularly clear in the surface velocity contrasts. The upstream part of the flow attains the highest velocity (XYZ displacements recorded by topometry), greater than 10 m/year and up to 20m/year in the central part of the B profile between the two previous *in-situ* crests *(4)* and *(7)*. The velocity decreases downstream (4 to 5 m/year at the lower shelf) but still remains highest in the axis of the flow, above the previous main gully of the 56' torrential basin (Malet, 1998). In fact, the present main intra-flowing gully is perfectly superimposed on the latter one (Fig. 4).

Thus the covered previous *in-situ* crests subdivide the flow in compartments identified either by morphological or hydrodynamical aspects. The paleotopography delimits stable or less active compartments (previous *in-situ* crests, western part of the B profile) from more active compartments (in the axis of the flow). Crest *(10)* influences the morphology of the flow ; on the C profile (Fig. 3 and Fig. 4) it acts as an obstacle to the downward progression of the moving material (velocity lower upstream and higher downstream, building of a shelf). This crest will probably emerge rapidly on the surface of the flow. Crest *(12)* plays the same role in building the lower shelf (E profile). Thus, only a future 3-D behaviour model can take into account this influence of the paleotopography on the behaviour of the flow.

6. Conclusion.

In general and especially in this case, earthflows require defining the 3-D subsurface structure in order to model landslide behaviour. Paleotopography can play a critical role both in the flow behaviour and in controlling the groundwater circulation or the mechanical characteristics of the material. Before developing an accurate model of the Super-Sauze earthflow, we still need :

- to extend the information on the paleotopography and the internal structure of the flow using geophysical investigations in progress ;
- to determine the hydrodynamical and rheological parameters of the active unit to assist in the choice of a behaviour law and model (viscous or rigid/plastic) ;
- to survey surface displacements (GPS and topometry), and to record climatic conditions and the position of the groundwater table ;
- to understand the factors predisposing slides and to identify the triggering processes of slides in black marl torrential basins.

These investigations are ongoing.

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