3.3 Report of the University Louis Pasteur Group

Edited by

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CONTENTS

3.3.1 Introduction

The French group at the University Louis Pasteur in Strasbourg[1] is involved in the second task of the Newtech programme, devoted to "Monitoring, modelling and predicting landslide activity".

The first contribution, in the context of task 2.1, was the draft of a technical paper entitled *"Landslides surficial displacements measurements: reliability of results obtained by topometry"* by J.-C. Flageollet, O. Maquaire and D. Weber.

In task 2.2, the French group's activities during the two years of the Newtech programme consisted mainly of field investigations on the Super-Sauze landslide. The existing equipment was supplemented by new material and numerous laboratory tests were carried out. Further results have been obtained by combining a large panel of methods and techniques. Figure 3.3.1 analyses the organisation of the team by its various research fields on this test site.

Topometrical Survey, GPS and Photogrammetry *D. Weber(1), L. Galisson (2),A. Bolley(3)*	Geotechnical investigations *J. Genêt & J.-P. Malet(1)*	Hydrogeological investigations *S. Velcin (1)*
Scientific co-ordination & Management of the NEWTECH programme and activities on the Super-Sauze landslide : *Prof. J.-C. Flageollet, O. Maquaire, D. Weber (1)*		
Laboratory tests *D. Hermann, S. Klotz (1)*	Geophysical investigation *M. Schmutz (1) and Y. Albouy(5), M Dietrich(7), M. Descloîtres(5), R. Guerin(6), J.J. Schott(4)*	Climatological aspects *Y. Sommen (1)*

(with specific collaboration of*
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(2) Ecole Nationale des Arts et Industries de Strasbourg (ENSAIS), Strasbourg
(3) Service Régional de Traitement d'Images et de Télédétection (SERTIT) Strasbourg
(4) Ecole et Observatoire des Sciences de la Terre (EOST), Strasbourg
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Figure 3.3.1. French team organisation and activities on the Super-Sauze landslide.

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In 1996 the main efforts were directed toward geotechnical investigations and several members of the CERG-ULP team took part in the field campaigns. New geophysical sounding investigations were started in May 1997. Newer and more accurate electric, electromagnetic and seismic sounding methods were applied on this test site in collaboration with the EOST.

Some new equipment also became operational: a climatological station, fully automatic and powered by solar energy, has been recording all the data for effective rainfall continually since July 1996. This equipment was installed at Super-Sauze, at a height of 1772 meters, very close to the landslide under study. In the summer of 1996 when the topometric network was reorganized two concrete pillars were erected in front of the moving mass to improve the topometrical survey of the landslide. In April 1997 a data-logger recording piezometric and tensiometric data in continuity on the landslide body also became operational.

Several contributors to the Newtech programme visited the Super-Sauze landslide during a workshop organised by the CERG (European Center on Geomorphological Hazards) in the Barcelonnette region. The French team's work on this site was studied during a field trip and was the subject of several lectures (Flageollet et al., 1996).

3.3.1.1 Geomorphological setting of Super Sauze landslide

The Super-Sauze is a winter sports resort 5 km. from Barcelonnette on the Enchastrayes commune's territory in the Restefond mountain mass, on the south slope of the Ubaye Valley (figure 3.3.2). The landslide affects part of the "Roubines" area, a 75 ha stretch of bad-land at the foot of two summits, the Chapeau de Gendarme (2685 m) and the Brec Second (2596 m). This bad-land developed in the geological context of black marls of the Callovo-Oxfordian layer, an autochtoneous formation (Photo 1) .

The crown, very spectacular, stands out between 1970 and 2150 m. in a predominantly North-South direction. The Sauze torrent rises at an altitude of 2070 m. at a place called "La Goutta", only a few meters behind the edge of the crown, at the base of the rock glacier, which is recognizable by its characteristic crescent shape. The main escarpment cuts into the moraine coverage (some ten meters thick) and the subjacent "in situ" black marls steep slopes, 100 meters high on average, corresponding to declivities of around 60°. Two very visible elements demonstrate this geological discord on the terrain: on the one hand, the light beige colour of the moraine material contrasts with the blackness of the marls. Secondly, a very marked break in the slope demonstrates the differently-balanced positions of two formations of different textures and degrees of granulometry. This superimposition also creates a discontinuity from a hydrological viewpoint. Immediately below this main escarpement the so-called "upper shelf" presents the appearance of a slightly rotational sliding mass. The reworked black marls, which include moraine blocks, then turn into a flow over a distance of almost 500 meters. The intermediate slopes on this section are some 20 to 25°. The relatively rectilinear profile is interrupted downstream by a slight convexity, labelled the "lower shelf". Finally the toe of the moving mass is situated at an altitude of 1743 metres, some 820 metres from the farthest point of the crown. In the upper part the flow is almost 200 m. wide, whilst the terminal fold narrows down to only ten metres or so.
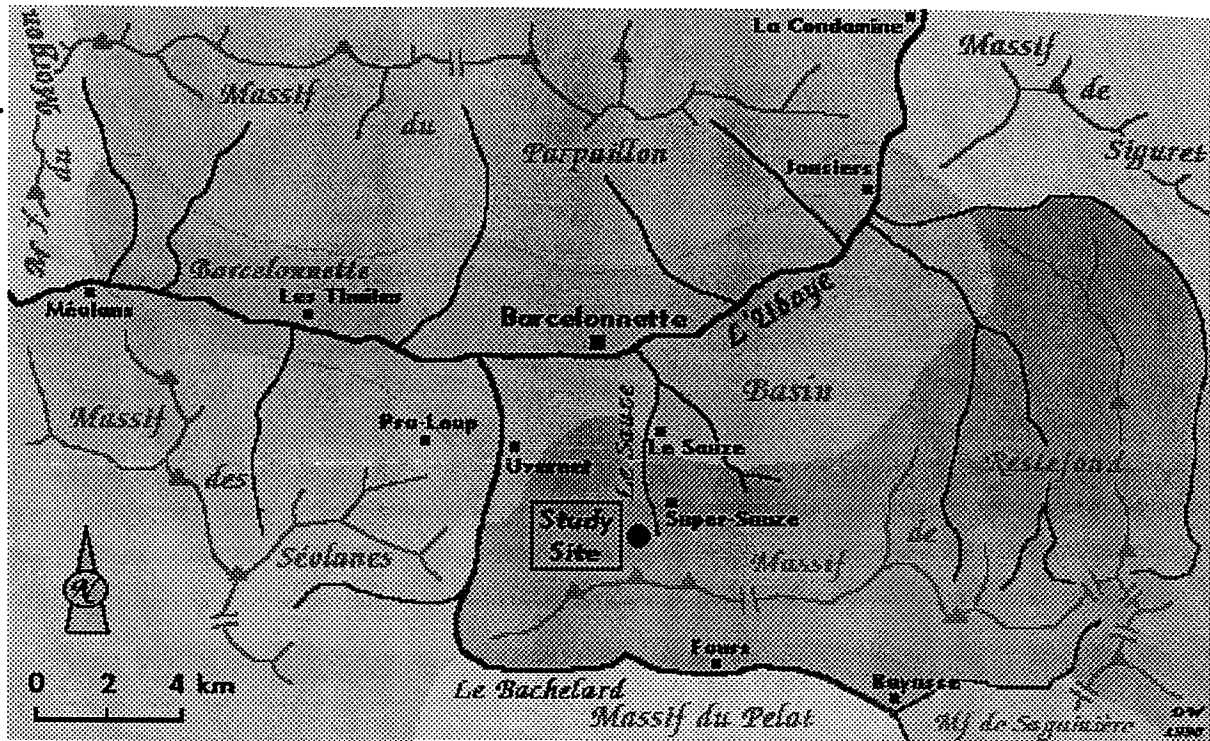
Figure 3.3.2 Location of the Super-Sauze landslide in the Barcelonnette basin.

3.3.1.2 Problems

The Super Sauze landslide is an example of the complex landslides occurring in clay or marl soils, with flows following a slide: there are many examples world-wide (Keefer & Johnson, 1983 ; Flageollet, 1988 ; Zhang et al, 1991 ; Dikau et al., 1996), including in France, and more particularly in the Oxfordian-Callovian « black lands » of the French pre-Alps. This means that the findings of this research can be extended to sites other than the one studied.

The conclusions drawn from measurements, tests and calculations on a similar, though larger, landslide, such as the one at La Valette (Colas & Locat, 1993 ; Van Asch & Nieuwenhuis, 1994) are interesting, but the simulations established from various behaviour models (fluid or rubbing) are far from being settled with observations on site. It seemed to us essential to complete the data used in the various models, in particular by introducing the geometric parameters of the landslide and the substratum and their geomechanical and hydrological characteristics.

As the preliminary geophysical observations had demonstrated the existence of several layers in the sliding mass, it was important to specify their number, thickness, extension and morpho-dynamic significance. Furthermore, as the preliminary geomorphological mapping had shown a paleotopography of ravines covered over by the displaced mass in certain places, we thought it essential to obtain accurate knowledge of this paleotopography and its role in the dynamics and the morphology of the moving mass. Did this mass behave like a sliding or a flowing land mass, a viscoplastic mass or a fluage, locally or throughout its extent and thickness? The investigations carried out in the context of Newtech sought to answer these questions.

Brec Second
2596m

Rock glacier

Crown

Main scarp

Upper shelf

Lower shelf

Toe

Photograph 1: Aerial oblique view of Super-Sauze landslide (by D. Weber, 1992)

3.3.2 The used methods and main results

3.3.2.1 Topometric survey of Super-Sauze landslide

There has been an ongoing topometrical survey of the Super-Sauze landslide since 1991 (Weber, 1994 ; Flageollet et al., 1996) and a high-performance second generation surveillance network came into operation in July 1996. The main innovation lies in the construction of two measurement stations in the form of concrete auscultation pillars with a drilled plate which centers the theodolite. These installations ensure high precision and very reliable measurements (Weber et al., 1998): Fifty points are distributed over the landslide and 15 around the edge of the crown. Most of the markers have been installed in accordance with the transects of the geotechnical investigations.

Nine measurement campaigns were organised during the Newtech programme. Figure 3.3.3 analyses the results in the form of displacements vectors over the surface of the unstable mass. These topometrical observations are in total agreement with those of previous periods and with the comparative photogrammetric interpretations of aerial pictures of 1988 and 1995.

With regard to the vectors, we see that the directions of the movements, both on the surface and at depth, depend on the paleotopography . The buried gullies and torrent beds are really «guiding» the reworked black marls. It is also interesting to observe that the new incisions made by the running water in the surface of the landslide body are superimposed on the paleo-flows.

The magnitude of the displacements measured during this period differs considerably from one sector to the other. Four classes of displacements can be determined :

- non-moving points;
- movements of less than 2 meters/year;
- movements between 2 and 5 meters/year;
- movements over 5 meters/year.

Around the crown there is no evidence of general movement simultaneously affecting all the markers placed along the edge of the main scarp. Three types of occasional instability are noticeable : falls of morainic blocks shifted from their surrounding matrix by streaming, rockfalls of black marls detached from the scarp by enlargement or widening of structural joints and bedding planes, and landslips of limited ground surfaces along the edge. This backward movement of the crown explains the disappearance of a shepherd's hut 5 meters from the edge some six years ago.

In the body of the landslide the zone recording the largest movements, 10 m/year and even more, is immediately below the upper shelf, where the slopes are the steepest and the material the wettest. Point number 45 for example moved of 28.80 meters between july 1996 and may 1998, i.e. an average speed around 15m/year (4 cm/day), and with periodic accelarations to 18 cm per day !

However, for the most part surface movements of between 2 and 10 m/year are recorded on most of the landslide body, depending on the slopes and the water contents. In the lower part of the flow, movements are in the range of 1 to 2 m/year, notably on the lower shelf and the toe.

GLISSEMENT DE SUPER-SAUZE
COMMUNE D'ENCHASTRAYES (ALPES DE HAUTE-PROVENCE)

Carte géomorphologique au 1/1000 ème
(Etat au 28 Août 1995)

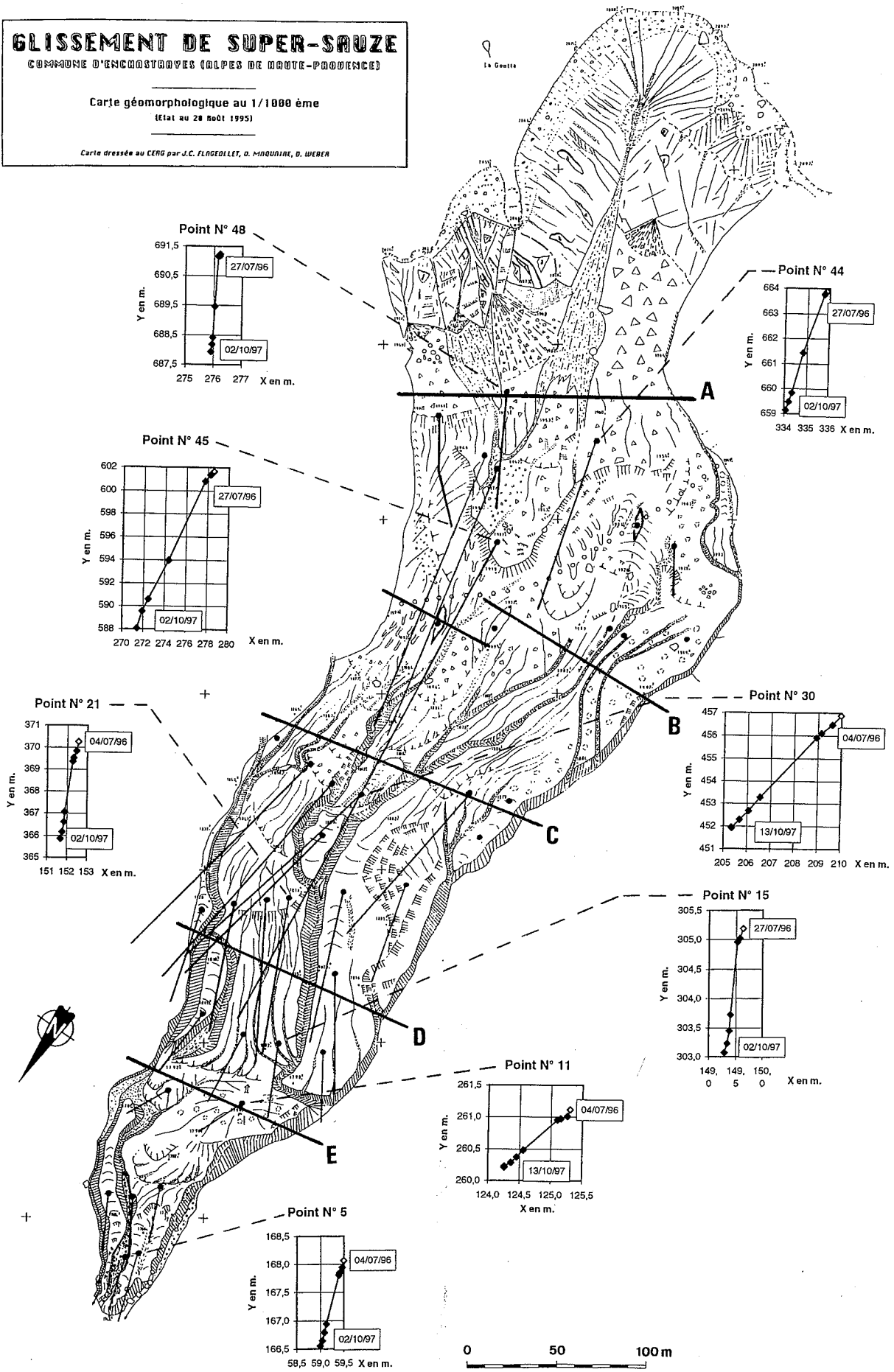Carte dressée au CERG par J.C. FLAGEOLLET, O. MAQUAIRE, D. WEBER

Figure 3 : Surficial displacements on Super-Sauze landslide.

3.3.2.2 GPS measurements

In July 1997 a GPS (Global Positioning System) measurement operation was organised in the Barcelonnette basin and more specificaly on the Super-sauze landslide. We used a Leica bifrequential differential system.

Four new geodesic points were installed around the Super-Sauze landslide, linked to the national IGN geodesic network. The connection between these points with the official network has been made for two points only (Barcelonnette and Pra-Loup) in planimetry, even one only (Barcelonnette) in altimetry, as this is the only one known to the nearest centimeter in the basin (the others are only known to the nearest decimeter). This is the first limit to the accuracy obtainable in a region by GPS if it is to be connected to an official network. The IGN has recently redefined its points to the nearest centimetre by GPS throughout the whole of France, which will enable these points to be set more accurately in future. One hour measurements per pair of points was applied, i.e. 8 hours. These points are determined in planimetry to the nearest 2 to 3 cm and to the nearest 5 to 10 cm in altimetry. A more complex geoid model suitable for use in the mountains would be needed to define these points more accurately, but this was not available for our calculations. The locations of these four points are thus recorded in two different systems, Lambert III and our own system of local locations defined on site by the topometric auscultation pillars.

These points can then serve as a groundwork to determine the detail points on and around the landslide. Two measurements methods may be used at this stage; the first, the « static » mode, requires a standing time of 5 to 10 minutes, the second, « stop and go » mode needs measurement times of a few seconds. With the « static » mode, it is theoretically possible to obtain over short distances (less a few kilometers) and under optimal field conditions a relative accuracy of 2mm +/- 2ppm in the position of a point.

- Measurement in « static » mode were made on points regarded as stable within the topometric network, normally taken by tacheometry. The object was to compare their locations as defined by GPS with those obtained by tacheometry during the same measurement campaign. These recordings also enabled us to determine the transformation parameters of the Lambert III system to our own local system on the Super-Sauze site. This experiment showed us that a small number of points on the surveillance network could not be identified permanently by GPS measures if they were sheltered by an over-large orographic or vegetal mask, or that they were not identifiable only for certain short periods when the satellite azimuths and elevations are unfavourable. This method of measurement was also used to position the setting points in the photogrammetric precessing.

- The « stop and go » mode enables us to determine a large number of points very rapidly to a few centimeters, sufficient for a geomorphological reading. The test consisted in following the edge of the main escarpment of the landslide in order to draw its shape. The results are good and promising for a full, detailed geomorphological reading.

This test campaign of GPS readings on the Super-Sauze site and generally in the Barcelonnette basin (the La Valette landslide) has shown the effectiveness of the tool in this study area. There are three major recommendations for future missions:

    - To familiarize ourselves thoroughly with the Ephemerides in order to work with optimal

satellite configurations and thus reduce the risk of finding points which cannot be calculated when returning from the mission because of poor signal quality;

- To reorganise the setting of the site's support points from at least three points on the IGN network which are known to the nearest centimeter in X, Y and Z;

- To recalculate the outline of the Super-Sauze site using a more complex geodesic model, more appropriate to the mountain terrain.

The respect of these three recommendations would allow measurements to the nearest centimeter in « static » mode, which would be extremely useful for a morphocinematic follow-up at least equivalent to that obtained by terrestrial topometry.

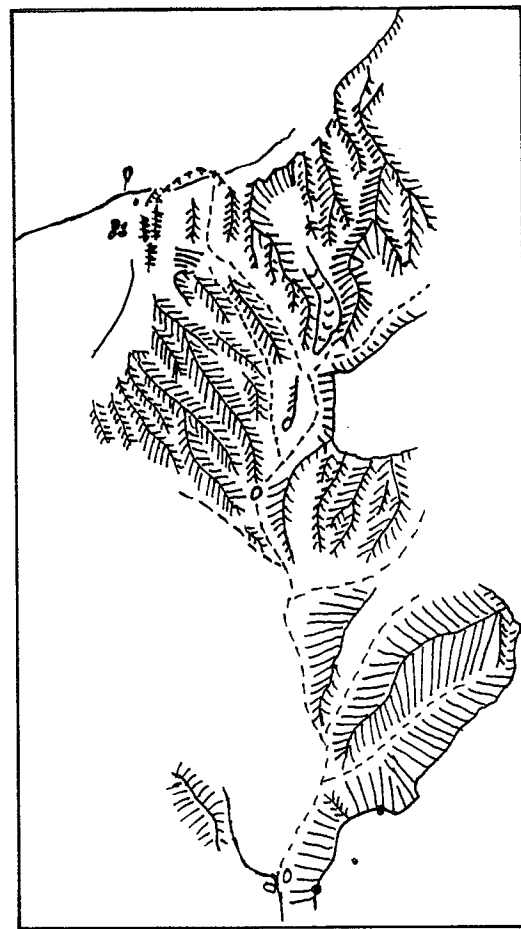### 3.3.2.3 Digital photogrammetric analysis

A digital photogrammetric treatment of six pairs of old aerial photographs has enabled us to cover the stages of the landslide's growth over the last 50 years (Weber & Bolley, 1998) in collaboration with the SERTIT (Service Régional de Traitement d'Images et de Télédétection). Six orthoimages, i.e. corrected for all geometrical deformations were generated at a resolution of 1 m from the photographs and six Digital Elevation Model (D.E.M.) with a resolution of 15 m.

The altimetric aberrations arising from the quality of the original numerised documents and the correlator's performance were corrected manually using the professional module of the orthomax software. This enables the visualisation in relief of a pair of pictures using liquid crystal glasses. Each picture of the pair is screened at a frequency of 120 Hz and each eye is masked alternately at the same frequency. Thus the left eye only sees the picture on the left and the right eye only the picture on the right, sixty times per second. The brain combines the two, which allows the relief to be perceived. The DEM knots are then superimposed on this relief representation. The association of the two information channels finally enables us to visualise the correspondence between the calculated relief (the DEM) and the relief given by the pictures. An editing tool then allows the DEM points to be moved manually so that they coincide with the terrain shown in the pictures. The percentage of points readjusted manually in this way is between 3 and 11% of the total number of points on each grid for the six DEM in this study.

The comparison of the various DEM presupposes that the models are adjusted with strict accuracy in relation to each other. For this reason the models have been reset a posteriori using data obtained during a recent campaign to measure the GPS (Global Positioning System). This operation enabled us to integrate some ten supposedly stable control points which were clearly identifiable on the various photographs and defined on the terrain to a planimetric accuracy of some 20 centimeters and an altimetric accuracy of a few centimetres.

The multitemporal analysis of the DEM provided various data on the geomorphological development of the landslide. In particular it established that a major movement commenced during the 1970s occurred between 1978 and 1982 (figure 3.3.4). A longitudinal profile across the unstable zone enabled us to identify clearly the ablation and accumulation zones of the terrain affected by the movement (figure 3.3.5).

SUPER-SAUZE LANDSLIDE'S EVOLUTION

Figure 4

1956　1971　1978　1982　1988　1995

Legend:
- active landslide
- crown, main scarp
- secondary scarp, fresh / indistinct form
- gully, ravine
- crack
- torrent / run dry
- spring
- block, boulder
- tree
- foot path
- farm road

N

0　m　200
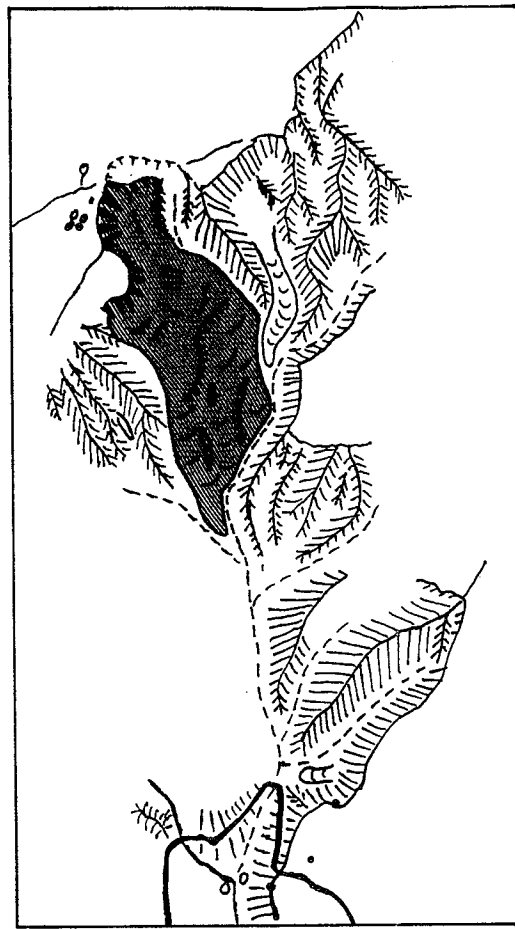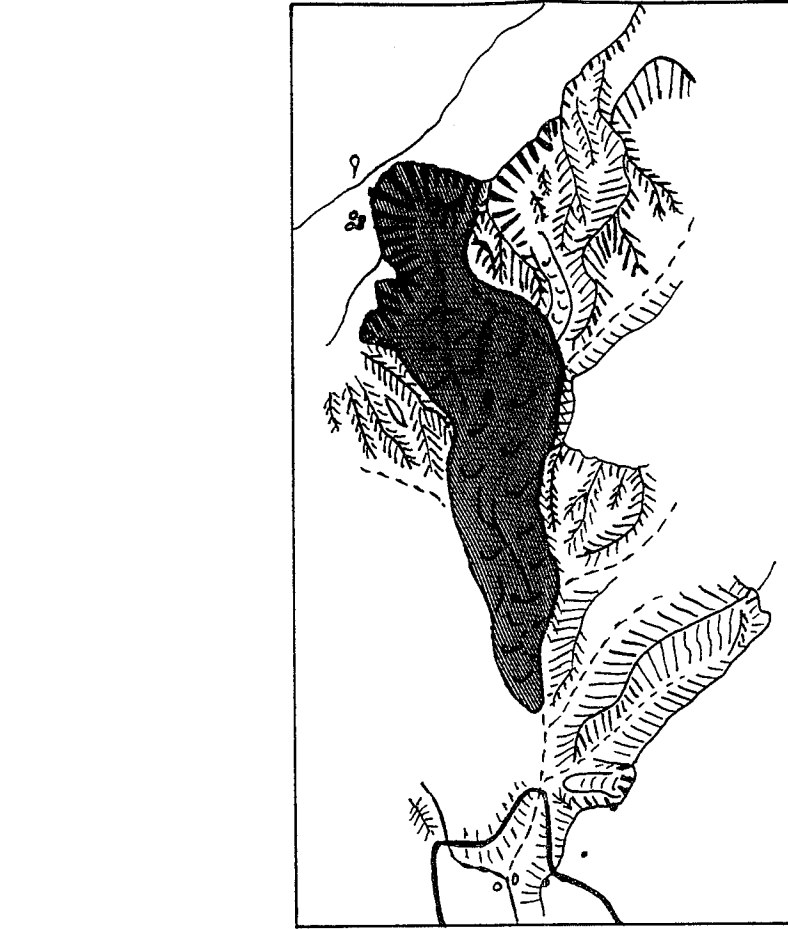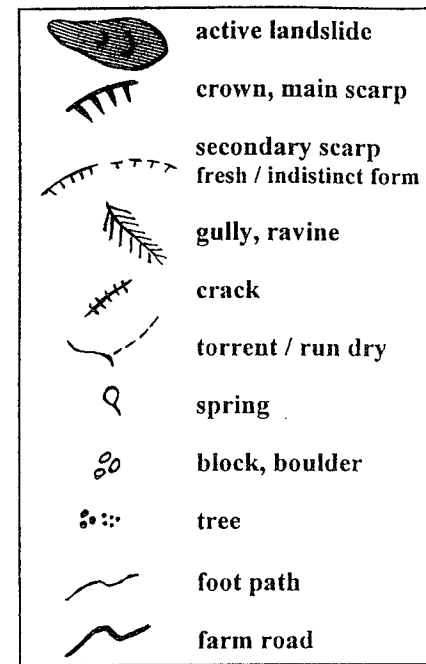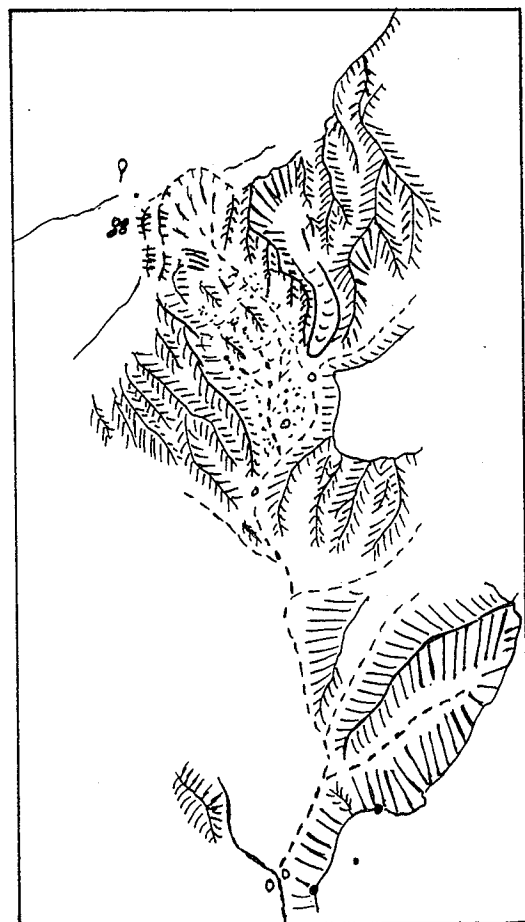
D. Weber, 1996
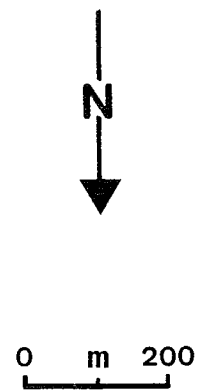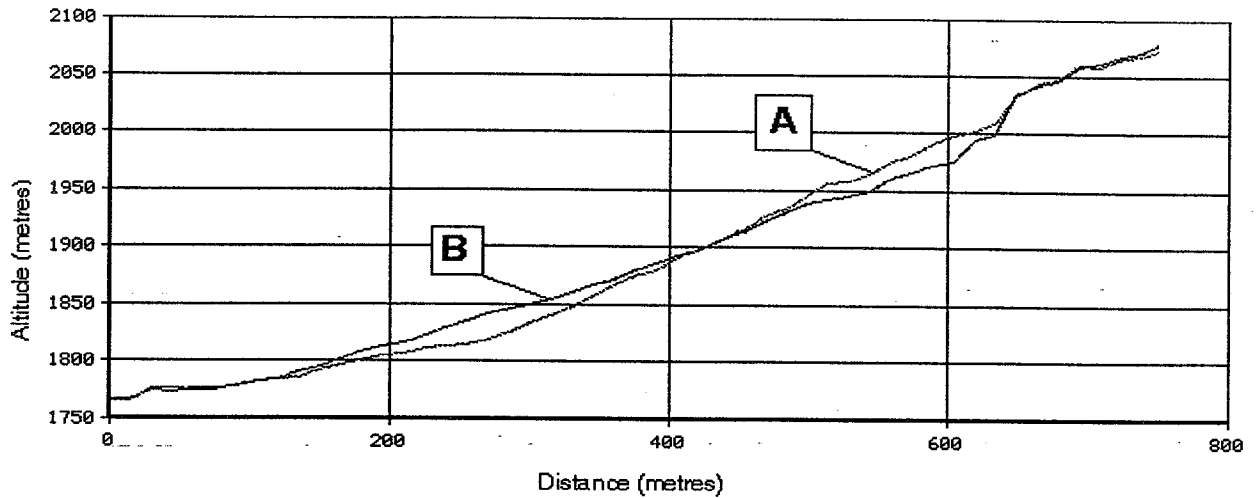
Figure 3.3.5. Longitudinal profile of the Super-Sauze landslide
   A : average profile of the 1956, 1971, 1978 D.E.M.
   B : average profile of the 1982, 1988, 1995 D.E.M.
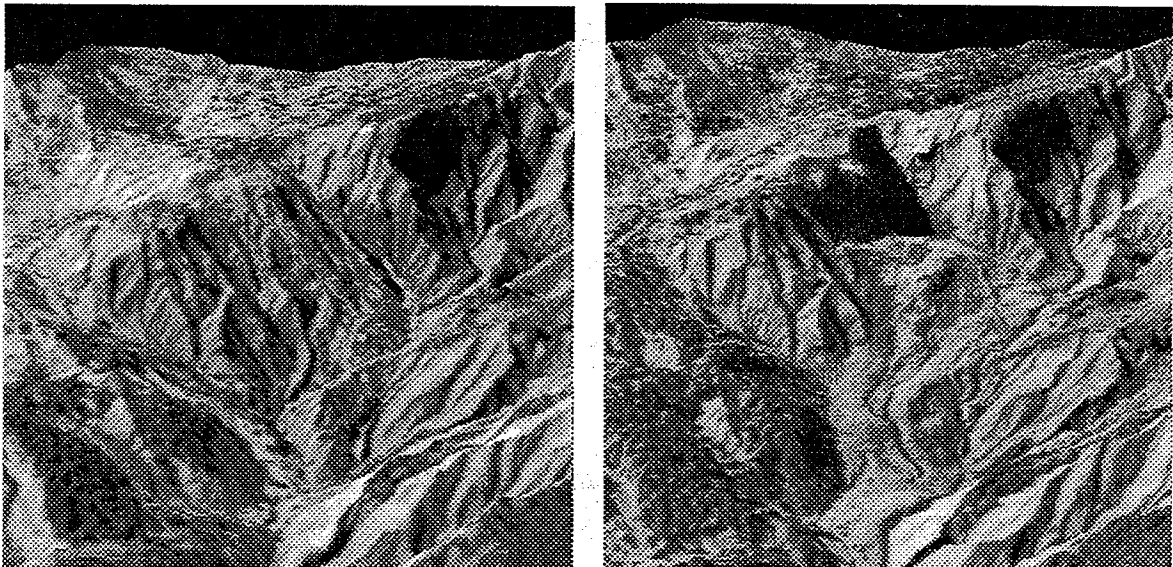
Figure 3.3.6. Oblique views reconstructed by digital photogrammetry.

The perspective views drafted (« draped » orthography on the DEM) for the various epochs enabled us to really « overfly » the landslide, both in time and space. They enable everyone, even non-specialists, to observe the morphological upheavals which have occurred on this site (figure 3.3.6). The left, in 1956, shows a slope with many ravines, one of which has already cut much deeper than its neighbours and the right, in 1995, being the flow-slide, close to its present physionomy.

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3.3.2.4 Geotechnical investigations

The geotechnical investigations on the Super-Sauze landslide have been organised in five transverse transects, noted A to E in table 3.3.1 and Figure 3.3.3. Area A is located on the upper shelf (altitude around 1950 m.) under the main scarp of the landslide, as profile E covers the lower shelf (altitude around 1800 m.) about a hundred metres upstream of the foot of the flow. The number of different investigations carried out are summarised in table 3.3.1, along with the various equipment installed :

Zone	dynamic penetrometer	percussion drilling	destructive parametred boring	core sampling boring	piezometer	inclino-meter	pressio-meter
A	14		2	1	1	2	11
B	26	6			8		3
C	26	3	3		10	1	
D	16	2			3		
E	19	2			10		
Total	101	13	5	1	32	3	14

Table 3.3.1. Geotechnical investigations on Super-Sauze landslide.

About a hundred dynamic drillings were made, either with a heavy DL 030 dynamic penetrometer apparatus comprising a 30 kg monkey, or with a light 10 kg monkey penetrometer in order to measure the resistances (Qd) of a rod driven into the soil and also to check the heterogeneity of the soil in depth.

Thirteen percussion drillings checked the soil-type and took intact or reworked 30 to 100 mm diameter samples to depths of from 0.70 to 7.00 metres (Total length = 49 m.). This test comprises driving a conical test wedge into the soil under known conditions (weight of monkey, rods, height of fall). We measure the depth for each drop of the monkey for a fall of 10 cm. The machines used are heavy and light penetrometers (30 kg monkey and 10 kg monkey) with a 35 mm probe tip. The rod diameter is only 22 mm, in order to avoid lateral rubbing over the length of the wall of the hole. We use the « Dutch » formula to determine the soil's resistance to the penetrometer probe tip (see Intermediate report).

The results are presented in the form of a pentogram on which the resistance of the rod Qd in Mpa (abscissa) is given as a function of the depth (ordinate). The characteristics of the penetrometer used are also indicated on this graph (figure 3.3.7). This test is easily mounted, quick and cheap. Because the equipment is relatively light we were able to use it in areas which were inaccessible for other tests requiring heavier equipment.

However, interpretation is difficult, as it is a 'blind' test. It should be used very carefully in stable saturated soils and in fine submerged soils. For these reasons several gaugings were carried out with pressiometric tests and destructive samplings whose parameters were recorded.

There were only 6 deep drillings spread over zones A and C during the two-week field campaign of September '96, owing to lack of funds. These operations were carried out by a
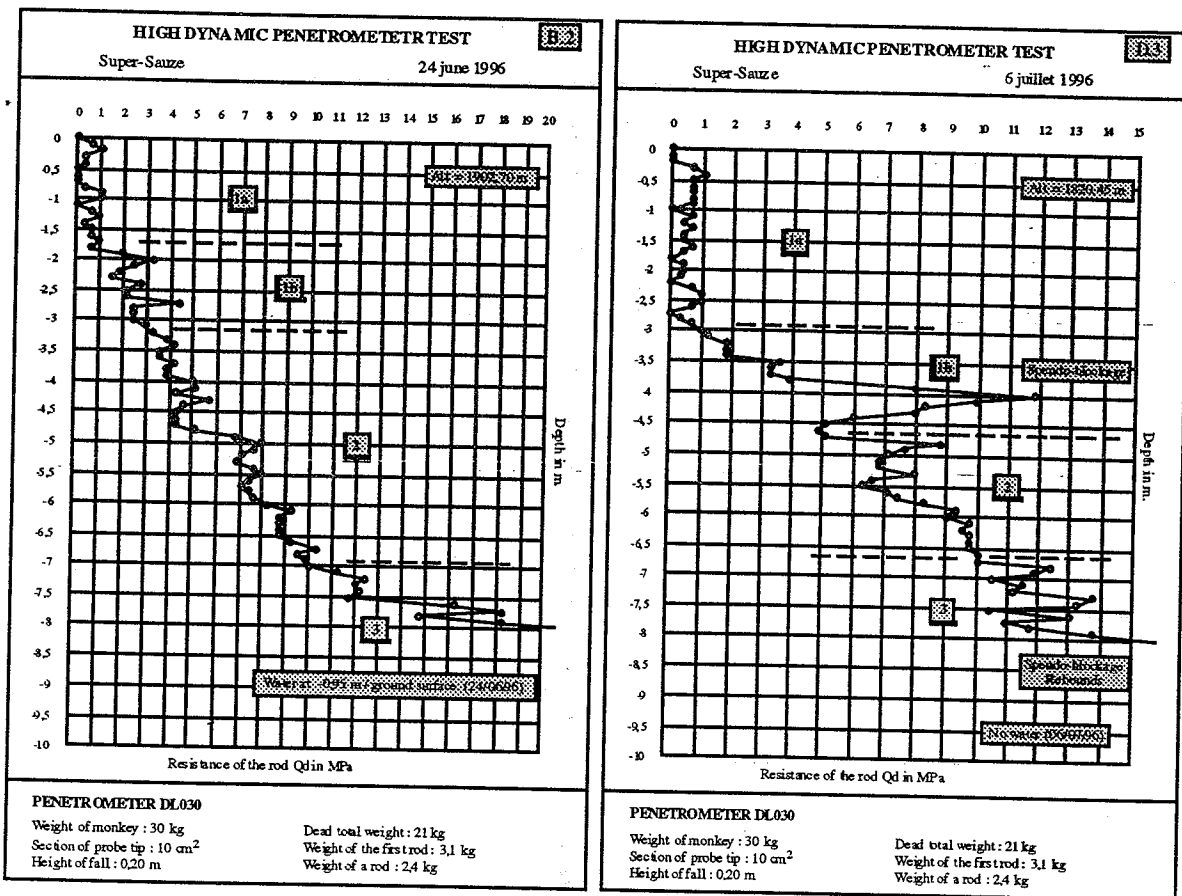
Figure 3.3.7. Penetrometric curves

specialised company using a powerful, high-performance NUZI 100 hp drill. Its weight and limited mobility on a scarped terrain called for expensive helicopter transport. The five destructive drillings with a diameter of 63 or 100 mm (tricone rock bit) depths varying between 18 and 29 metres, extended over a total length of about 120 metres. Various parameters were recorded during these drilling operations: advance speed, pressure on the tool, injection pressure. Because of the disappointing results observed (due to the decomposition of the marls by the injected water necessary for drilling) only one core sampling bore was made, over a length of 13.50 metres and 116 mm diameter.

We were able to carry out various tests and install equipment in these boreholes; these included 32 open piezometers of various diameters (25 mm, 40 mm and 50 mm), to various depths and protected with gravel filter (0.03/0.06) or filtering sock and bentonite stopper (ring +/- 30 cms thick). Three inclinometric tubes enable us to detect the depth of the rupture surface and to measure the movements over the vertical profiles and we were able to measure the « in situ » geomechanical characteristics of the soil as a result of ten pressiometric tests [pressiometric module (Em), flow pressure (Pf) and pressure limit (Pl)] (see intermediate report).

The main results provided by the geotechnical investigations appear in a simplified way in table 3.3.2.

layer n°	nature	thickness (m.)	Qd (Mpa)	Pl (Mpa)	Em (MPa)	seismic waves velocity (m/s)	Penetration speed (m/s)
1a	very soft wet mud	0.5 to 3	< 1	?	?	400 to 750	> 125
1b	soft wet mud	0.5 to 4.7	< 3	< 0.3	<5		
2	clay hard consistancy	0 to 5	3 to 8-10	0.3 < Pl < 4	5<Em<25	1000 to 1800	10 to 125
3	compact clay or "in situ" marls	depth at .5 to 18 m	> 8 blockage	Pl > 4	>25	2000 to 3700	< 10

Table 3.3.2. Geotechnical and geophysical parameters measured on Super-Sauze landslide.

The first point to be noted and stressed is that three main layers were identified:

Layer 1, on the surface or under a layer of approx. 10-30 cm varies in thickness from 2-3 m to more than 7 m. Except in special cases where a pseudo-blockage has been recorded, we can state that the thickness of this layer is correctly defined overall. It is a reworked and fairly heterogenous marl formation with a fine, damp matrix. A few small blocks of marl in an advanced stage of deterioration are buried in it. They show on the penetrograms as small peaks of local resistance.

In very wet zones we can distinguish a sub-category for which there is almost no resistance to the rod, the weight of the rods being sufficient for penetration. This is liquid mud.

Layer 2 is heterogenous and shows many resistance peaks. It, too, is made up of reworked marl, but deterioration is less advanced and it is drier and more compact than the first layer. It contains many blocks of marl, stable but deteriorating. There are a few small layers, very thin, and small flows occur in them. The thickness of this layer is very variable.

Layer 3 is a stiff, compact formation, consisting of marl either in solid blocks or with a slightly eroded surface. The penetromer was blocked fairly quickly in this formation. This layer is only formally identified in a few drillings because of many early blockages over a block of moraine or calcite.

In conclusion, we can state that the formation of accumulation comprises two superimposed layers, the first being very wet viscous mud and the second rigid/plastic, more stable and more compact. Furthermore, as observed previously, these two distinct layers contain marl blocks of various sizes, their degree of instability being more advanced downstream. We can offer an indirect explanation for this. It is important to note that, overall, the penetrometer drillings carried out in the lower part of the mudflow, starting at profile D, reach greater depths than those carried out upstream. Pseudo-blockages and localised resistance peaks within a single layer are more numerous, as in the upper part of profile A, for example. This arises partly because there are fewer moraine blocks and partly because of greater instability in the marl blocks in the reworked formation.

We can present the following interpretations for the landslide body from a geomorphological standpoint. Figure 3.3.8 shows a cross-line profile of investigation transect B.

Unit 2 : "viscoplastic" behavior when saturated. "elastoplastic" behavior on the bottom.

- Thickness : 2 - 5 meter.
- Resistance : Qd < 8 - 10 MPa.
- Pressiometric modulus E_M : 5 - 15 MPa.
- Pressure limit P_L : 0,3 - 4 MPa.
- Semi-impervious layer : K = 10^{-5} to 10^{-8} ms^{-1}.
- W_L = 26 - 35 % ; W_P = 13 - 18 % ; W_R = 12 - 16 %.
- Plasticity index I_P = 13 - 19.

Unit 1 : "viscoplastic" behavior.

- Thickness : 3 - 4 meter.
- Resistance : Qd < 3 MPa.
- Velocity of displacement : 8 - 10 meter/year.
- Pressiometric modulus E_M < 5 MPa.
- Pressure limit P_L < 0,3 MPa.
- Pervious layer on surface : K = 10^{-2} to 10^{-6} ms^{-1}.
- W_L = 30 - 40 % ; W_P = 13 - 18 % ; W_R = 12 - 16 %.
- Plasticity index I_P = 10 - 23.
- Variable ground water table.
- Traction's cracks.

Unit 3 : "elastoplastic" behavior "dead body".

- Thickness : 5 - 8 meter.
- Resistance : Qd > 10 MPa.
- Velocity of displacement : stable.
- Pressiometric modulus E_M > 15 MPa.
- Pressure limit P_L > 4 MPa.
- Impervious layer : K = 10^{-8} to 10^{-11} ms^{-1}.
- No water.
- Thin compacted argillaceous material.

W

E

Western compartment

Central compartment

Eastern compartment

In-situ marl crest

1905 m

1900 m

1895 m

0 m   50 m   100 m   150 m   200 m   250m   300 m

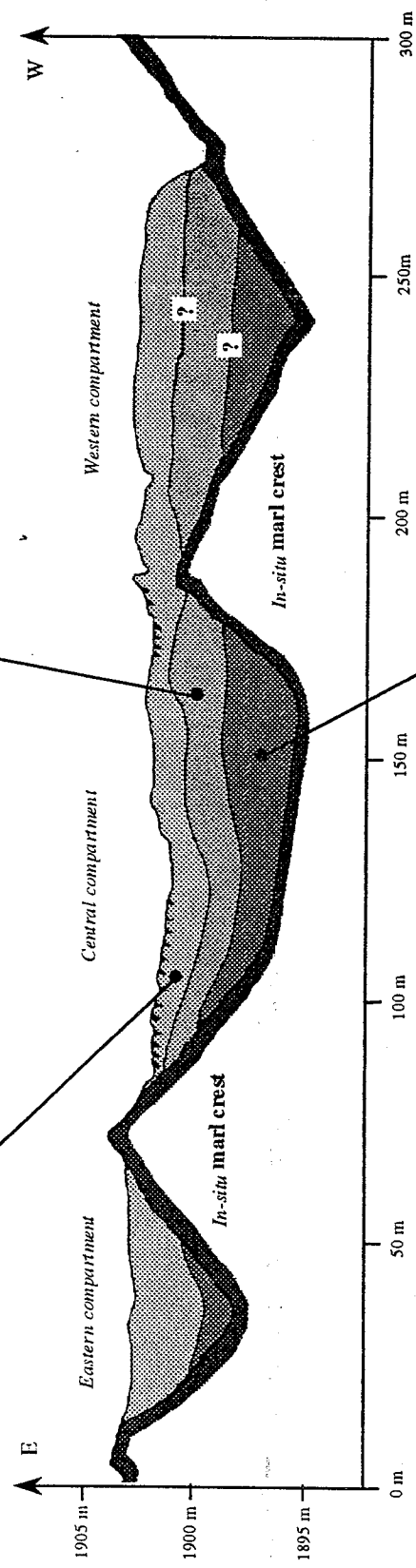© MALET Jean-Philippe, UFR Géographie - Strasbourg. 1998.

Figure 3.3.8. Profil B.

On profile B, field observations identify two crests of "in situ" marls emerging from the moving mass : there are very interesting facts concerning the paleotopography which we intend to ·reconstruct. The structure of the landslide body is quite well known in that sector following the 1996 investigations. Some uncertain limits remain in the middle part of the profile (X from 100 to 140) : the forthcoming geophysical soundings and perhaps some complementary penetrating tests should provide the missing information on that point within the next few months. There are two possible options at present ; the upper limit proposed is given by the drillings and penetrometer tests, the lower option by one seismic-refraction sounding made in October 1995. The shapes of the landslide bottom are more or less the same in the two options, confirmed by the interpretation of old photographs; the uncertainty lies in the depths of this limit. A similar question remains near the western border where we were unable to reach the bottom with our penetrometers. On the whole of that area the three and even the four layers (1a, 1b, 2 & 3) were well identified. That is not the case in the eastern side of the body, especially between the two emerging crests where the surface material was too wet allow us any penetrating tests. The few which were possible on the borders of these wet sectors give us a good idea of the slopes, but it was impossible to distinguish the different layers of reworked material.

On profile C (figure 3.3.3), in the middle of the length of the landslide body, three deep destructive drillings enabled us to establish the paleotopography at 16 to 20 meters depth. The limits between the different layers of reworked material are also clearly identified. There was considerable blockage or pseudo-blockage of the probe tip in this area during penetration tests, due to a large amount of morainic blocks. Two inclinometers were installed on that profile.

The bottom of the moving mass on transect D is estimated at depths varying from 10 to 15 meters, depending on the shape of buried topography. Below the lower shelf (cross-line E) the thickness of accumulated material is about 8 to 9 meters in the eastern part and 6 to 7 meters in the western part.

3.3.2.5 Hydrological and hydrogeological investigation

A first important point to underline is the predominant part role of the paleotopography in the water circulation through the landslide body, in the three dimensions. Data on permeability and transmitivity were obtained by different methods. First a serie of 8 infiltration tests were carried out on the surface using the double ring method. Because of the fissurations and cracks in the upper layer of the soil, results are very heterogeneous, with Ks from 10^{-4} to 10^{-7} m/s. "Lefranc" tests (by emptying the tube and mesuring the filling-up time) on reworked material layers (depths between 0 and 4 metres) show low permeabilities from 10^{-7} to 10^{-10} m/s, i.e. transmitivity figure of $7.3*10^{-6}$ m^2/s. One "Lugeon" test on the "in situ" marls (by injection under pressure) gives a very low permeability value, around $2*10^{-9}$ m/s. The "terres noires" formation, when undisturbed and "in situ" can be considered as impermeable.

Water inflows were observed during the drillings at different depths at almost all sinkings. The levels were followed up at the time in relation to the climatic conditions using open piezometric tubes pierced at different depths. In the months following these installations measurements could only be taken from time to time when we were in the field. A data logger connected to a pressure captor and four tensiometers has provided continuous readings of those hydrological parameters since the end of April 1997. In future we will be able to use

these measurements and the permeability tests designed by Lefranc and Lugeon to confirm the existence of the following:

- a more or less continuous subsurface circulation with piezometric levels between 0.50 and 1.50 from the topographic surface. These levels fluctuate fairly slowly by a few centimetres a day, with pluviometric response times of several hours. Lefranc tests for drainage show low permeability of the order of 10 -6 m/s. This longitudinal circulation is partly channelled by the paleotopography clearly visible in the profile B sector. The deepest gullies collect this water , lowering the lever of the « table » (acting as a drain). This drainage is particularly easy to see in dry periods.

- a discontinuous circulation level at the depths within the compact reworked layer or at the interface with the first layer. In three of our piezometers this level is 3 - 4 m. from the surface and the pulsations seem very feeble.

- an impermeable marl in situ, without any inflow of water during sinkings. The trench dug along the spur of the gully and located on profile B shows the reworked, muddy (and therefore very wet) formation flowing over the very dry marl. The Lugeon test by injection under pressure shows very low permeability, less than 10^{-8} m/s approx.

The surface drainage axes comprise, firstly, the gullies and the intra-flowing gullies and secondly, mixed flow-marl gullies in situ which have cut into the banks of the flow. The first type have an intermittent flow directly related to rainfall episodes, particularly during storms (taken up and dried out rapidly). The second are perennial, though the flow varies greatly with the season and the pluviometric conditions.

Their role is significant in several respects both in drainage, as noted earlier, and more particularly in their erosive action. The latter carries a solid and appreciable load mainly during flooding, with two possible consequences: the first in terms of the balance between the quantity of incoming and outgoing material (supplied from the main scarp), the second in terms of maintaining the instability, in particular on the western edge of the flow.

3.3.2.6 Laboratory tests

The various field campaigns organised on the Super-Sauze test site provided numerous samples which were used for several kinds of laboratory tests (see intermediate report).

The results obtained from those tests are summarized in the table 3.3.3.

	Wl (%)	Wp (%)	Wr (%)	Ip	Wn (%)	CO_3Ca (%)
number	20	20	19	20	88	21
min value	26	13	12	10	4	20
max value	39	18	16	23	18	45
average	31	16	14	15	13	34

Table 3.3.3. Atterberg limits, water & CO_3Ca contents.

The CO_3Ca contents measured on the 21 samples analysed are heterogenous (variation rate of 21 %) but moderate, from 20 to 45 %, with an average of 34 % only. Thus, the "Terres noires" of the Super-sauze landslide are clearly defined as argileous marls.

The Atterberg limits determination gives the following statistical results : the liquid limit (Wl) varies between 26 and 39 % for an average of 32 % ; the plastic limit (Wp) extends from 13 to 18 % with an average value of 17 % ; the shrink limit (Wr) goes from 12 to 16 % for an average of 15 %. Near to Wp, it indicates that the material is not very sensitive to shrinking. Finally the plastic index (Ip = Wl - Wp) varies between 10 and 23 for an average of 15. When we compare those limits with the natural water contents (Wn), we can see that the liquid limit is never reached and that most of the values remain below the shrink limit.

The couples (Wl, Ip) reported in the Cassagrande diagram show a cloud of points centered around 32 % for Wl and 15 for Ip : According to Cassagrande classification, the Super-Sauze "Terres noires" clearly belong to the Ap group, "low plastic clays". However, the variation rate of 22% for Ip demonstrates that the material sifted at 400 μm does not show a homogenous reaction. This can probably be explained by a higher clayed fraction.

The average specific weights are around 21,4 kN/m^3 for wet material and 19 kN/m^3 for dry material.

The variability of the clayey part can be explained by the initial state of the material analysed (more or less weathered) and by the protocol applied , but above all by the quantity, as they are heterogenous; the results obtained for a large quantity ($\gg$10 kg) are more realistic than those obtained for small quantities ($\ll$ 1 kg).

Sample n°	Weight kg	$\ll$ 80 μμ %	$\ll$ 2 μμ
C1	182	16	3.5
C2	82	36	10
E	4.5	58	14.5
1996 Number of samples		19	10
mini	small quantity ($\ll$1)	28	7
maxi	id°	90	32
average	id°	64	19

Table 3.3.4. Granulometry.

With regard to permeability, laboratory tests on intact samples gave Kv (vertical permeability) in the same range as those measured by the field tests : from 6×10^{-6} to 2×10^{-8} m/s.

Shearing strength on Super-Sauze landslide material cannot be tested for the moment. Different values can be found in the literature, in particular those published by Phan (1993) who differentiated reworked black marls of the wet and dry material from the Barcelonnette basin: he proposes values for c from 7 to 10 (wet) and from 3.6 to 34 (dry) and angles for **phi** from 28 to 39° (wet) and from 35 to 43° (dry). These figures agree with the values published by Antoine et al. (1995) for the "Terres noires" in the southern French Alps.

3.3.2.7 Geophysical investigations

Preliminary measurements of seismic refraction and electrical resistivity have been taken in the context of the European TESLEC programme, mainly in the form of Schlumberger probes (Schmutz, 1995 & 1996, Flageollet and al., 1996). They demonstrated the advantage of combining two methods (Brodde & Fufa, 1989; Cummings & Clark, 1988; DUTI, 1985, McCann & Forster, 1990; Palmer & Weisgarber, 1988), but also their limitations in a 1D interpretation. However, a pole-pole cartography over a small representative sector showed that 2D and 3D investigations methods are preferable, because of sizeable material variations and above all because of the damaged topography of the surface (Pous et al, 1996). Furthermore, in the work carried out in the NEWTECH context the investigations were carried out systematically in 2D and 3D.

Methods

During 1997 the B and C transects of the Super-Sauze landslide were prospected by using all the geophysical means at our disposal in order to compare results. Three additional measurement techniques were used, these being the TDEM (Time Domain Electro Magnetism), induced polarization and conductivity on sample.

The TDEM is relatively new to Europe for sub-surface applications. It owes its basis to Wait (1951) and Velikin and Bulgakov (1967); Kaufman and Keller (1983) developed its theoretical aspects and its operational aspects were developed by McNeill (1994). Among more recent references the following may be quoted: Das, 1997 ; De Hoop, 1996a & 1996b ; Duckworth, 1997 ; Rabinovitch, 1995 ; Descloîtres et al., 1995, 1997 ; Descloîtres et al., (submitted). It was put into operation on the Super-Sauze using the ORSTOM (Bondy) apparatus (with the co-operation of the Department of Applied Geophysics of the University of Paris 6) . The main advantage of this inductive method, which is consequently very sensitive to conductive terrains, lies in its power of penetration, which is higher than that of direct current methods, whilst using less space. Its application to earth movements lies in its capacity to detect the roof of the substratum; however it remains less accurate in distinguishing the layers within the sliding mass.

Induced polarization is the only geophysical method which can detect the presence of disseminated metallic minerals or clays, but the physical techniques for rocks are essential in determining the influence of the clay resistivity as compared with that of the soil. We were therefore obliged to extend the research to include determining the influence of the various parameters which could affect the resistivity of the whole of the rock.

These three methods, combined with the geophysical resistivity methods, will enable us to arrive at the variation in electrical resistivity as a function of the water content.

Results

• Seismic

Two direct and inverse profiles were recorded on transects B and C using detonating cord as the seismic source, which gave an excellent relationship between signal and noise over all the distances considered (up to 150 m between source and receiver), thus allowing us to determine the arrival time of the first waves refracted along the landslide interfaces without any ambiguity. Furthermore the series of shots fired within and outside the devices enabled us to

obtain a multiple coverage of the refraction interfaces. On the two layers detected (figure 3.3.9, figure 3.3.10) the first seemed to be quite restricted as compared with the seismic and ·geotechnical results. For the second, the wide lateral variations of the milieu required additional data to take account of the lateral variations in speed over the length of the profiles.

• Time Domain Electro Magnetism (TDEM)

The first tests enabled us to establish what size transmitter coil to use, a 5m coil, taking account the depth of the investigation required and the precision of the picture. The ideal offset for this coil size is 12.5 m, and the gain and the frequency of the receiver coil is 237.5 Hertz.

We carried out two probe profiles on the C transect with 5 and 10 m coils.The profile made with the 10*10 was used to compare and confirm the tests. The results obtained with the 5 x 5 coil correspond closely with those provided by geotechnical reconnaissance. On the other hand, with a 10 x 10 coil the thickness of the flow was under-estimated and areas of high resistivity appeared which are difficult to interpret at the present stage of our investigations.

The interpretation from the 5 x 5 coil (figure 3.3.11) closely reflects the reality between the distances 42.5 and 110 m. However, probes close to ravines do not enable us to define the flow, as they seem to be in a resistivity transition zone. Additional measurements are planned in order to define the limits of the landslides at the edges of ravines. These initial results confirm that TDEM is a preferred method for studying a landslide provided the appropriate coils are used. Furthermore, the method is relatively easy to put into operation.

• Electric

We carried out four parallel lines (one being in « inverse profile » perpendicular to the landslide) and fourteen azimut probes on the B transect, for a 3D interpretation and an optimal characterization of the area studied.

The results of C profile from the 1D interpretation are given in Figure 3.3.12. The electrical inerpretation corresponds to the geotechnical results (Genêt et Malet, 1997) for most of the probes, i.e. we see a difference in resistivity between the reworked marls of the first layer (20-40 Ω.m), the second layer (40-80 Ω.m), and the marls in situ place (greater than 100 Ω.m). On the other hand, the interpretation of a few probes which did not correspond to the geotechnical results may be explained by the effects of typography and significant surface heterogeneity, which can be eliminated by a 3D interpretation

• Induced polarization

A significant signal was observed on the C transect. In most of the PP probes the chargeability exceeded mV/V (between 4 and 7 mV/V) for depths of the order of 10 m.

• Physic of rocks

At the outset we had to check if they were comparable with the sample. Comparisons between interpretations of measurements of electric resistivity in situ and resistivity measurements on sampling were satisfactory. The influence of the saturation rate on the conductivity of the sample was assessed by increasing the electrical conductivity as compared with the saturation rate for 2 samples. The operations were satisfactory for a given interval of the saturation rate.

Seismical interpretation of the C profile

Legend:
- landslide's topography
- lower limit of layer 1
- lower limit of layer 2

Elevation (m) vs. Receiver's localization on C profile (m)

Figure 3.3.10. Seismical interpretation

Seismical interpretation of the C profile

Legend:
- landslide's topography
- lower limit of layer 1
- lower limit of layer 2

Elevation (m) vs. Receiver's localization on C profile (m)
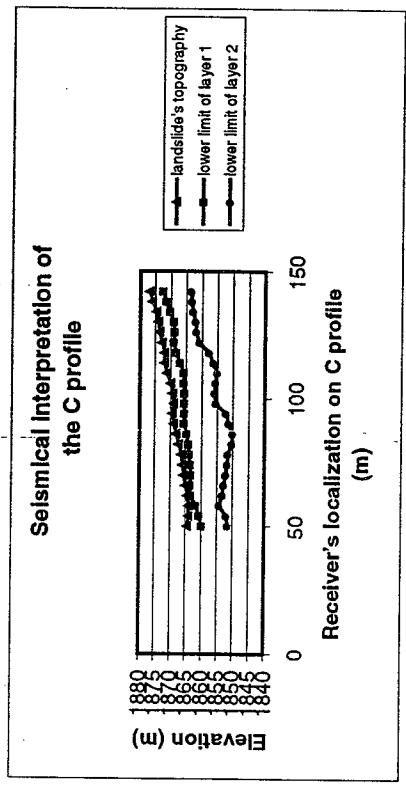
*** : zone of non interpretable soundings

Figure 3.3.12. Electrical interpretation

Geotechnical measures on the C profile

Legend:
- landslide's topography
- lower limit of layer 1
- lower limit of layer 2

Elevation (m) vs. Sounding's localization on C profile (m)

* zone of pseudo-blockages tests

Figure 3.3.9. Geotechnical measures

Geotechnical measures on the C profile

Legend:
- landslide's topography
- lower limit of layer 1
- lower limit of layer 2

Elevation (m) vs. Sounding's localization on C profile (m)

** : resistivity transition zone

Figure 3.3.11. TDEM interpretation with 5*5 coil

3.3.3 Synthesis : A qualitative model for triggering and evolution of the landslide

We have been able to classify this landslide into the category of flow slide and to present a qualitative model for the triggering and the development of the landslide flow as a result of investigations, pictures, morphological readings and the follow-up of development since 1991.

3.3.3.1 Triggering model

This is based on the way in which a rupture occurred recently on a hogback shaped crest situated less than a hundred metres from the Super-Sauze landslide at the height of the ablation zone. The information collected about this zone, its downstreaming and the shape of the rupture surface makes it possible to apply the rupture mode observed in the crests to the landslide.

How a ravine's crest ruptures

This crest cracked during 1997 without any visible previous warning over a length of approximately 80 m at an altitude between 1850 and 1900 m. Figure 3.3.13 shows that at present several more or less disconnected blocks are bounded by wide, deep, open vertical or oblique fractures. This rupture starts upstream with a vertical escarpment around 7 m high, and shale and fracturation planes can be seen along its length. The surfaces of the disconnected blocks are more or less crumbled over a thickness of several decimeters.

On figure 3.3.13a the initial topographic profile of the crest has been reconstructed from slopes measured upstream and crests close by. The progressive opening of structural fractures has occurred because of gravity and decompression, assisted by the infiltration and the development of harmful interstitial pressures in the damp season. The marls in situ in this crest have therefore been cut into several fairly voluminous blocks. There is also a possibility of a progressive rupture starting at the base of the slope, due to undercutting by the stream.

Four blocks have slipped 5 or 6 m over an irregular surface made on the previously existing structural plane. Verification of the instability by calculation called for the use of « push-stop » models (Fig. 3.3.13b) or even 3D rupture models. At this stage of the investigation we were only seeking the scale, assimilating the surface of the landslide to a rupture circle passing by the summit and the base of the dislodged part (Fig. 3.3.13a). For zero cohesion and internal friction values of 40° the safety margin by the Bishop method is only 1.454. In addition to respecting the precise geometry of the rupture surface, it would also be necessary to take account of the part played by the water in the open fractures to bring the value of F below the unit.

Application to the Super Sauze landslide

The topography prior to the landslide corresponded to the parallel crests and ravines, similar to the present topography of the rest of the basin beyond the landslide. This paleotopography still exists, fossilized very high upstream under the sliding masses, as shown in figure 3.3.14, which shows the three successive positions of three deep drill bits, established by tacheometry and GPS on 15 October 1996, 2 May 1997 and 2 October 1997 - the fore drilling at a depth of 13.50 m and two destructive drillings parametered at a depth of 28 m and 28.80 m. The drill

alt. (NGF) NNE SSW

1900 m

cracks rupture plan

schistosity planes

Previous profile

(A) **Before rupture (beginning 1997)**

1890 m

Stability calculation (Bishop's hypothesis) :

$c' = 0$; $\varphi' = 40°$; $\gamma = 20$; no water : $F = 1,454$

4

breaking up of several blocks

1880 m

3

Infiltration : water filled cracks & pore pressure increased during the wet season.

1870 m

Ground surface (october 1997)

2

structural pre-existing beds forming rupture and sliding surfaces

1860 m

erosion by torrent

circular slide for safety factor calculation

1

progressive rupture ?

0 m   10 m   20 m   30 m   40 m   50 m   60 m   70 m   80 m

alt. (NGF) NNE SSW

cracks main scarp

Previous profile

(B) **After rupture (end 1997)**

1900 m

schistosity planes

1890 m

flacks

4

44°

dislocated block

1880 m

Ground surface (october 1997)

rectilinear slide on a pre-existing structural bed

1870 m

3

desintegrated blocks on surface

displacements of trihedral blocks along pre-existing surfaces

crumbling blocks & flaking off

1860 m

2

thrust-support model

20°

erosion by torrent

© MALET Jean-Philippe, UFR Géographie - Strasbourg, 1998.

1

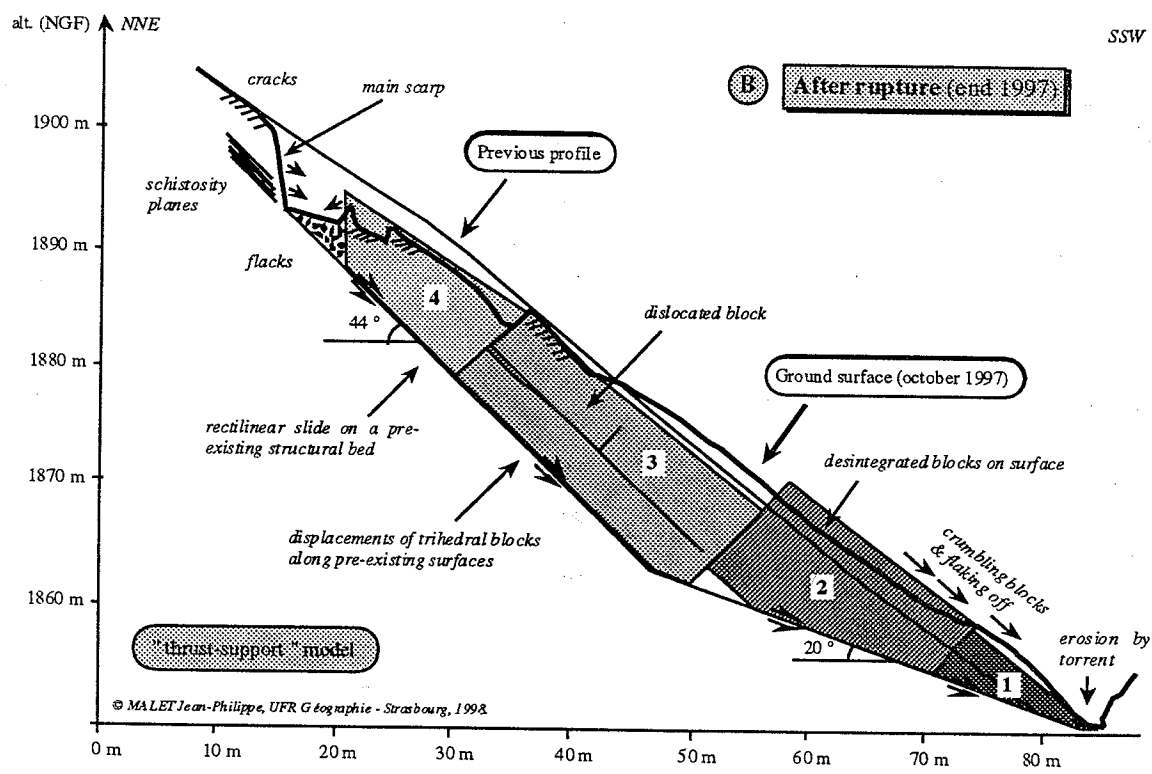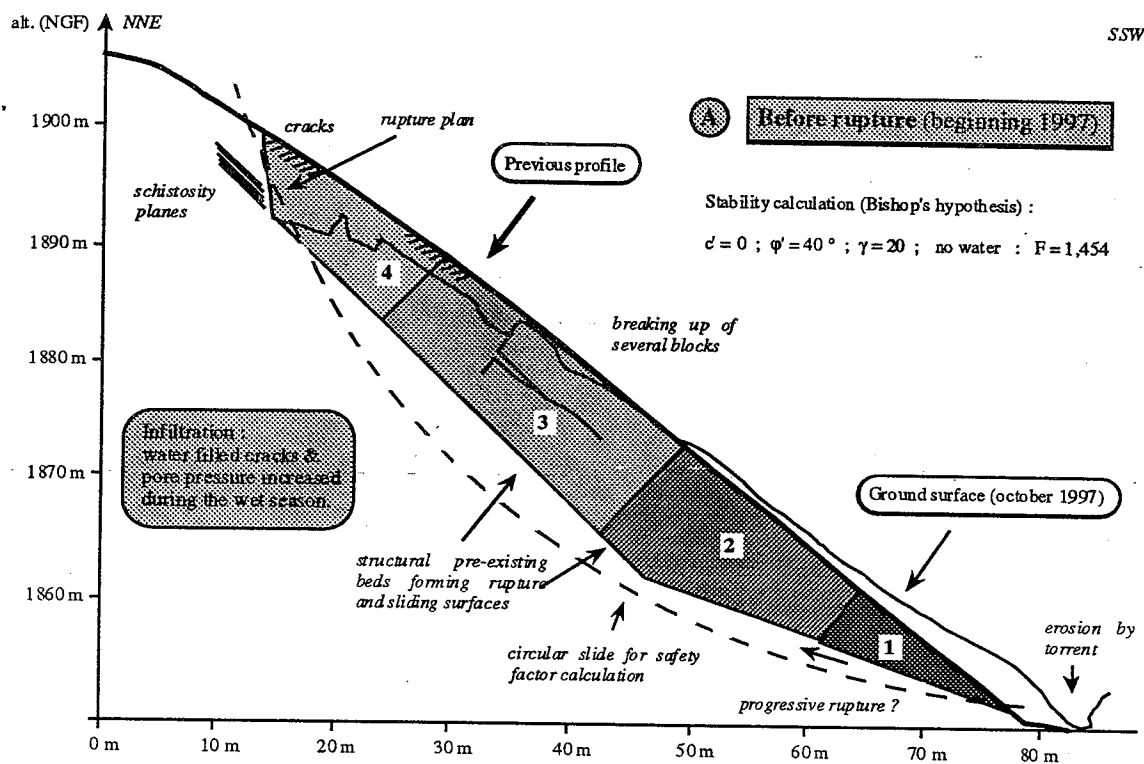0 m   10 m   20 m   30 m   40 m   50 m   60 m   70 m   80 m

Fig. 3.3.13. Rupture model of a interfluve crest between two ravines

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holes were fitted with inclinometric tubes (FI over the whole depth, i.e. 13.50 and EP8 up to a depth of -12.90 m only, because of difficulties in inserting the tube) and with a piezometric ·tube (EP5). We were able to define the boundary between the ablation zone and the accumulation zone on the A transect using the results provided by geotechnical reconnaissance (probes and inclinometric measurements), the follow-up of surface movements and the morphological data taken from the aerial photographs. The following are marked on the figure 3.3.14 : the approximate limits of the ravines (crests 5 and 6 and the bottom of the ravine) shown on the ortho-rectified aerial photographs taken in 1956 (before the landslide was triggered); the line of cut AA' pointing in the direction of the movement vectors.

The paleotopography is almost perpendicular in the direction of the movements. It is fossilized by a heterogenous argile and marl formation with weak geomechanical characteristics (see earlier). The ablation zone is thus situated upstream of profile A and its downstream limit is quite close, between the foot of the main fossilized escarpment and this preserved paleotopography on profile A. The initial landslide occurred in the crests, the structural planes guiding the rupture (figure 3.3.15).

3.3.3.2 Development model

In the 1950s (figure 3.3.15 A) the first dislocations of the crests and ravines occurred as a result of numerous fracturation planes which are still clearly visible on the main escarpment and there was an accumulation of material on the talweg. Progressively, with subsequent occurrences (figure 3.3.15 B), the topography levelled (crests more or less truncated) and fossilized by the accumulation, in which blocks of marl or moraine can be seen. In the 1950s,the earliest dislocations of the crests occurred and the material accumulated on the talweg; these dislocations were due to the numerous fracturation planes which are still clearly visible on the main escarpment. Progressively, with succeeding events (figure 3.3.15 B) the topography levelled (more or less truncated crests) and fossilized by the accumulation, in which blocks of marl and moraine can be seen. Structural landslides then followed the shrinking of the river basin which takes the form of a circle bounded by a steep escarpment on the plan. At the same time the accumulation flow progressed downstream, covering several crests.

In the 1980s (figure 3.3.15 C) the flow progressed faster than it was fed by the small blockfalls and clastes from the main escarpment, though a shrinking of the crown was nevertheless measured. The consequence of this negative balance is a draining of the accumulation zone with a subsidence of several meters in the upper part and the emergence of crests like those visible at present along transect B. This drainage mainly affects the superficial part of the sliding mass.

Movements of the upper layer upstream have reached 5 to 12 m/year in an approximately north-south direction in seven years. The thickness of the material affected is of the order of 8.50 m according to the F1 drilling, which shows the division between the reworked terrain and the marl in situ. Below the speed is unknown but it does not seem to be negligible, given the movements and the deformations recorded on the EP8 inclinometric tube between 15.10.96 and 2.5.97.
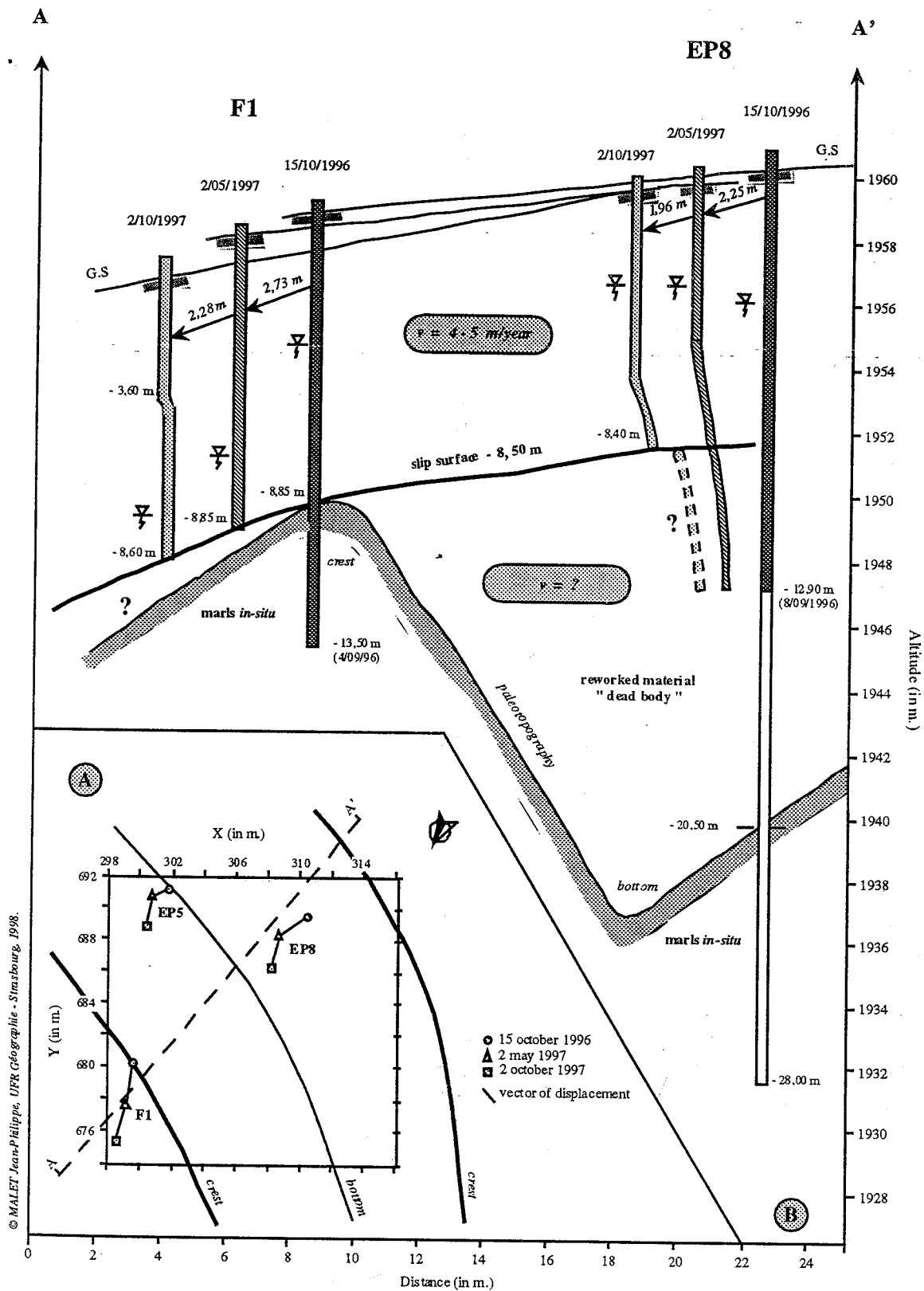
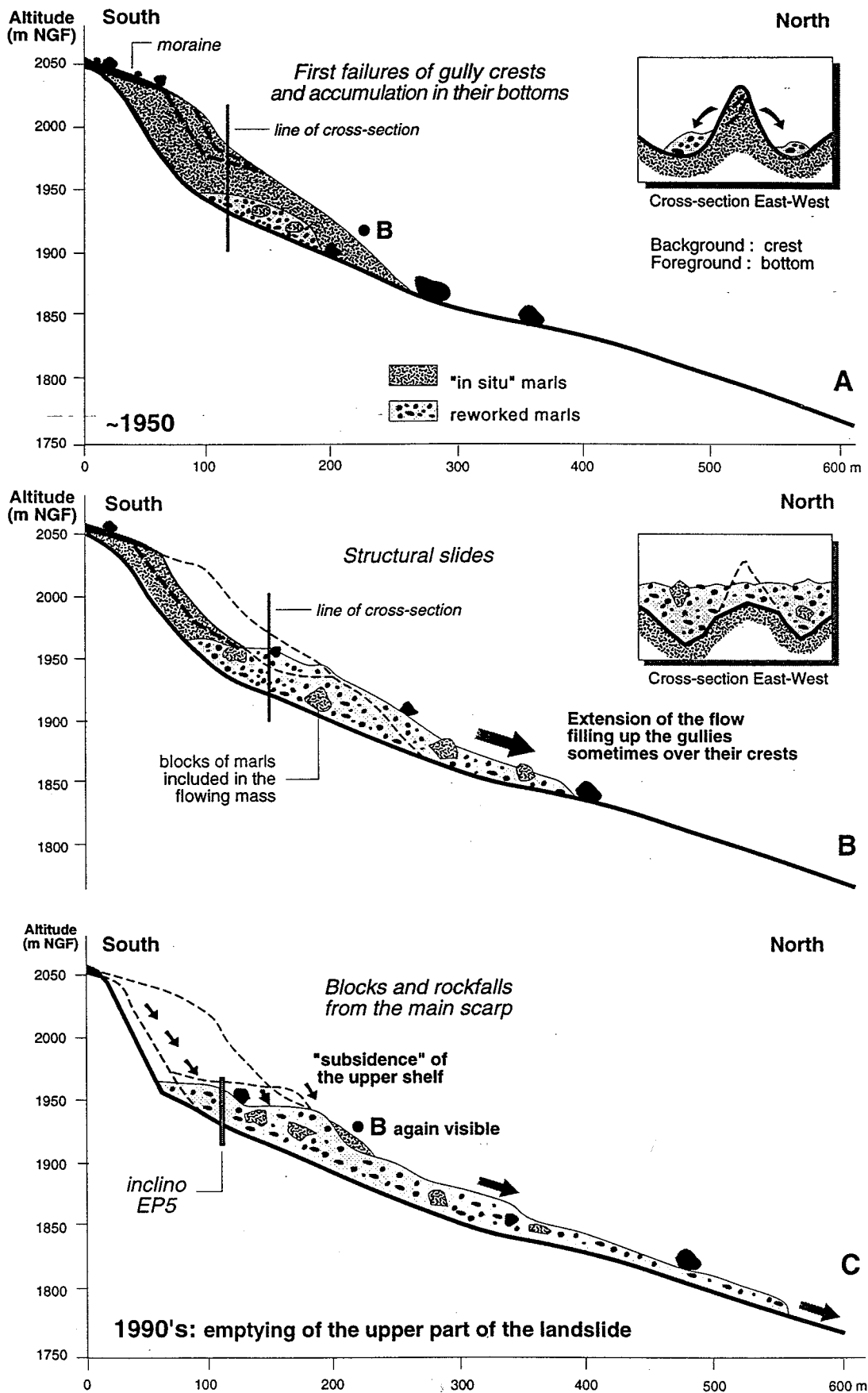Figure 3.3.14. Location of drillings and paleotopography

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Altitude (m NGF)

South   **North**

moraine

First failures of gully crests and accumulation in their bottoms

line of cross-section

● B

2050
2000
1950
1900
1850
1800
1750

Cross-section East-West

Background : crest
Foreground : bottom

"in situ" marls
reworked marls

~1950

A

0   100   200   300   400   500   600 m

Altitude (m NGF)

South   **North**

Structural slides

line of cross-section

2050
2000
1950
1900
1850
1800

blocks of marls
included in the
flowing mass

Cross-section East-West

**Extension of the flow
filling up the gullies
sometimes over their crests**

B

Altitude (m NGF)

South   **North**

*Blocks and rockfalls
from the main scarp*

**"subsidence" of
the upper shelf**

● B again visible

2050
2000
1950
1900
1850
1800
1750

*inclino
EP5*

1990's: emptying of the upper part of the landslide

C

0   100   200   300   400   500   600 m

DAO A.B. CEREG CNRS

Figure 3.3.15. Evolution of the Super Sauze landslide

3.3.4 Conclusions

,The French team devoted the two NEWTECH years to in-depth research on the Super-Sauze flow slide, and to two aspects in particular:

First, the paleontology fossilized by the moving mass, its shape, its depth and the internal geological structure. This was achieved by combining several techniques, some of which were new and rarely used on a landslide and even less often used in synergy. This combination was both direct (drillings, penetrometric soundings, inclinometric, topometric, piezometric and tensiometric measurements) and indirect (geophysical soundings, photographs interpretations). We now have valuable data on the tridimensional structure and the hydrological functioning of the unstable mass, which have enabled us to construct a qualitative mechanical model showing how this landslide was triggered at the outset and how it developed.

Secondly the development of the movements. As a result of the considerable improvements in instrumentation on the site the climatological and hydrological data are now recorded continuously. The topometrical survey of the landslide will also be continued at a minimal pace of one measurement per month. This information will be used in the near future to establish the statistical relationships between rainfall, piezometric variations and landslide superficial displacements for the Super-Sauze test site.

Research on this type of landslide, so widespread in the black marls of the Alps, was started before the two-year NEWTECH programme and will continue afterwards. On the one hand, new geophysical techniques will be tested and applied so as to establish precisely the three-dimensional picture of the landslide's « geometry » and structure. Secondly, for prevention purposes, the physical parameters measured in the field will be used to choose and and construct a determinist model of its development and in particular the possibility of the flow's transformation into a torrential lava.

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