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The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC)

FINAL NATIONAL REPORT (JUNE 1996)

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by

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CONTENT

FOREWORD

This report has been written by J.C. Flageollet, O. Maquaire and D. Weber, with the collaboration of A. Amiot, S. Kirchhoffer, B. Martin, L. Quintlé, M. Schmutz and M. Nelson, from works made by the Strasbourg's team (Fig. 1) during the last two years (1994-1996) in the Barcelonnette area for the TESLEC project in collaboration with the "Institut de physique du globe" of Strasbourg.

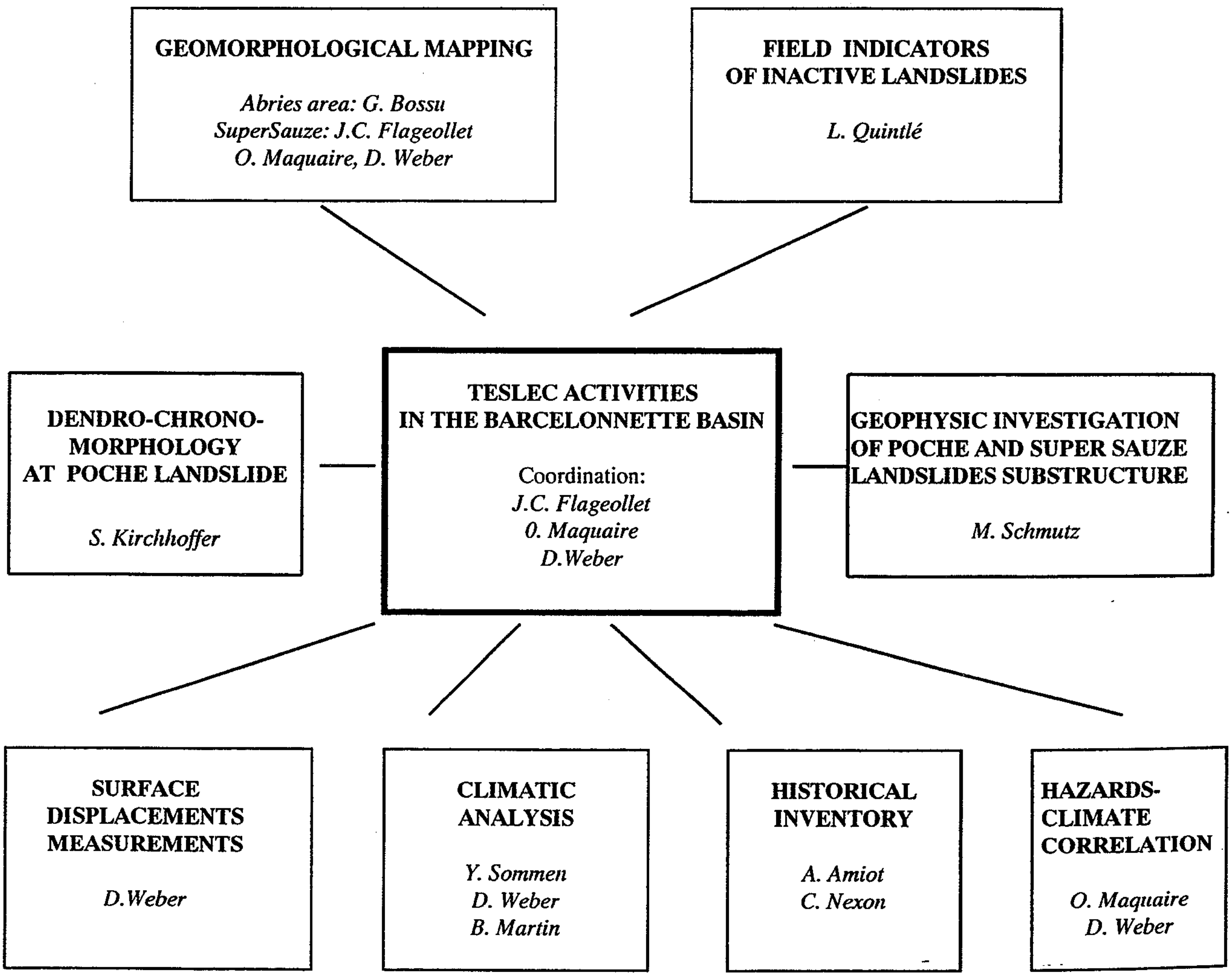


Fig. 1: Strasbourg's team Organisation

Objective N° 2

PAST DISTRIBUTIONS OF LANDSLIDES AND THEIR RELATIONSHIP TO CLIMATIC CHANGE PARAMETERS. QUALITATIVE EVOLUTION MODELS (LANDSLIDE AND LANDSCAPE EVOLUTION)

INTRODUCTION

The whole of the basin is less than 13 km from east to west and 10 km from north to south; nevertheless it has several active landslides as well as many unstable sectors (Fig. 2).

The spatial concentration of these phenomena in this region can be explained by the conjunction of various unfavourable factors, in particular the presence of black marl, which is both very erodable and very prone to landslides. The triggering and continuation of these land instabilities is due both to climatic factors and to changes in land use over the last two centuries.

I. GEOMORPHOLOGICAL MAPPING OF BARCELONNETTE BASIN

Two types of mapping have been carried out :

- we have made a geomorphological map of the basin on a scale of 1/10 000, like that of the Abriès valley,

- a detailed geomorphological map of the landslides on a scale of 1/1000 (for example, the Super Sauze landslide in object no. 3).

II. RESEARCH INTO GEOMORPHOLOGICAL INDICATORS FOR THE RECOGNITION OF OLD AND PRESENT LANDSLIDES

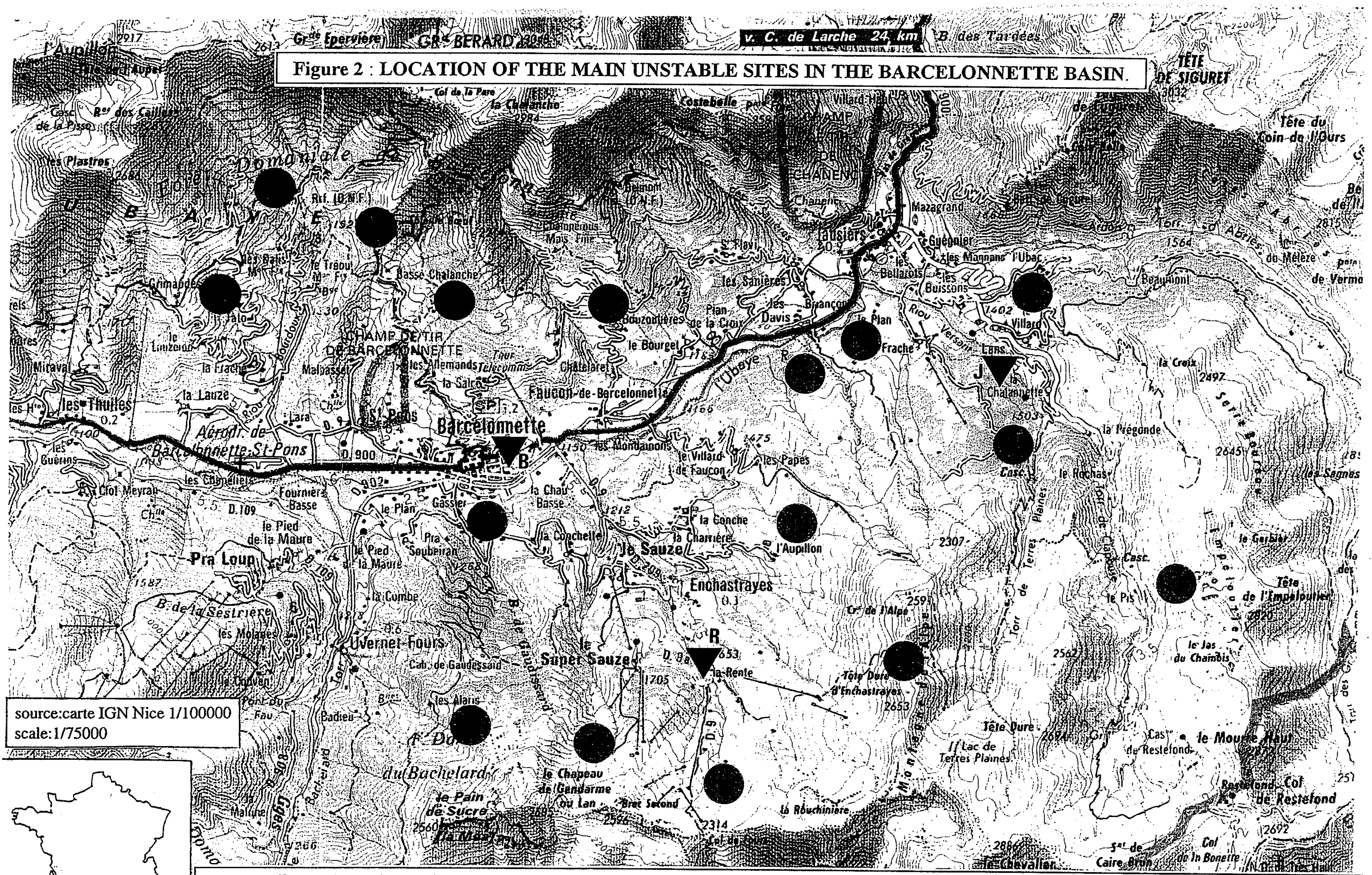
At present there are four large active landslides in the basin, visible to the eye, measurable, measured and named :

- the Poche landslide flow (triggered before 1924),
- the Super-Sauze landslide flow (triggered around 1940),
- the Valette landslide flow (triggered in 1982),
- the Bois Noir landslide (triggered in April 1993),

not to mention numerous small slides of torrent banks.

Written records mention other earth movements in the 19th and at the beginning of the 20th centuries and direct observation ot the topography leads us to interpret many details as outlines of movements, more or less eroded by rainfall or effaced by reforestation, agriculture and stabilisation works.

Figure 2 : LOCATION OF THE MAIN UNSTABLE SITES IN THE BARCELONNETTE BASIN.



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1:Bouzon's combe. 2:Aiguettes ravine. 3:Pra Bellon. 4:La Valette. 5:Bouzoulières road. 6:Poche & Ribes streams. 7:Le Plan. 8:Lans. 9:Le Pis. 10:La Frache-Bois Noir. 11:Chamoussières rock. 12:l'Aupillon. 13:Routres ravine. 14:Super-Sauze. 15:Les Alaris. 16:Jalet (Gaudissard stream).
Climatological stations : **B**: Barcelonnette (1140 m.). **J**: Jausiers-Lans (1510 m.). **R**: La Rente (1678 m.)

Old landslides, dormant or active, are located and numbered by registering the type of shapes in detail, by locating their juxtaposition and analysing its meaning.

2.1. Detailed registration of shapes and analytical study

This register was made using:

- IGN topographical maps, scale 1/25 000 3539 (East Jausiers-Le Sauze, 1991 edition),
- the BRGM geological map of Barcelonnette, scale 1/50 000 (XXXV-39, BRGM 1974 edition),
- aerial photographs, IGN 3534-3639, scale 1/30 000 (Mission Barcelonnette-Larche, 1988),
- Library documents,
- direct field observations.

The categories of forms listed are :

1°) steep slopes, the value, orientation and outline of which may correspond to former primary or secondary landslide. Wherever possible we try to distinguish « escarpments » of structural origin (layers or limestone strata in soft marl).

2°) embossments, dents, and intermediate hollows which could be old accumulated excrescences.

3°) Changes in embankment direction and the perpendicular profile of the hydrographic network, which are not connected with the structure.

4°) The position of trees. Since reforestation at the beginning of the century the oldest trees have been subject to movement, which they have resisted, and they lean in various directions. Redressment betrays this former activity. The forest zones affected can only be located by direct examination.

For the south slope of the basin which is the subject of this work these four categories of forms have been located on four maps (Fig. 3 & 4) on the same scale (morphological indicator maps).

2.2. Analysis and drafting of a map giving the (probable) sites of old landslides

1°) By superimposing the four indicator maps we are able :

- to reconstitute the apparent limits of old landslides from upstream to downstream, following the morphodynamic « logic » : escarpment and ablation, accumulation, flow, ...

- to assess the degree of presumption of an old landslide: if all four types of outline are present there is a very strong presumption, if three are present, there is a strong presumption; if there are only one or two the presumption is weak or very weak. In this way, we establish a probable localisation map.

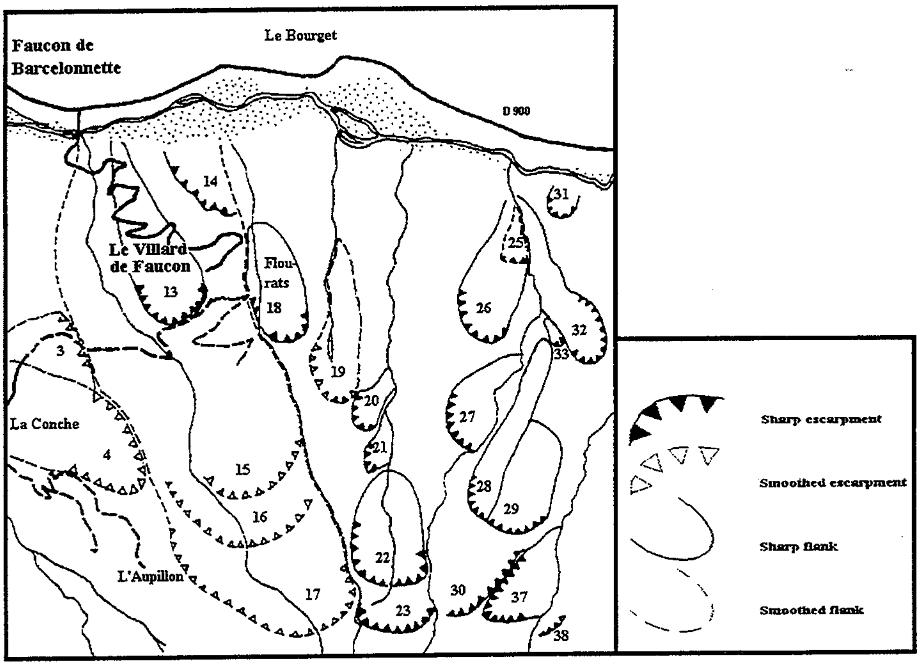


Fig 3a : Location of escarpments and flanks.

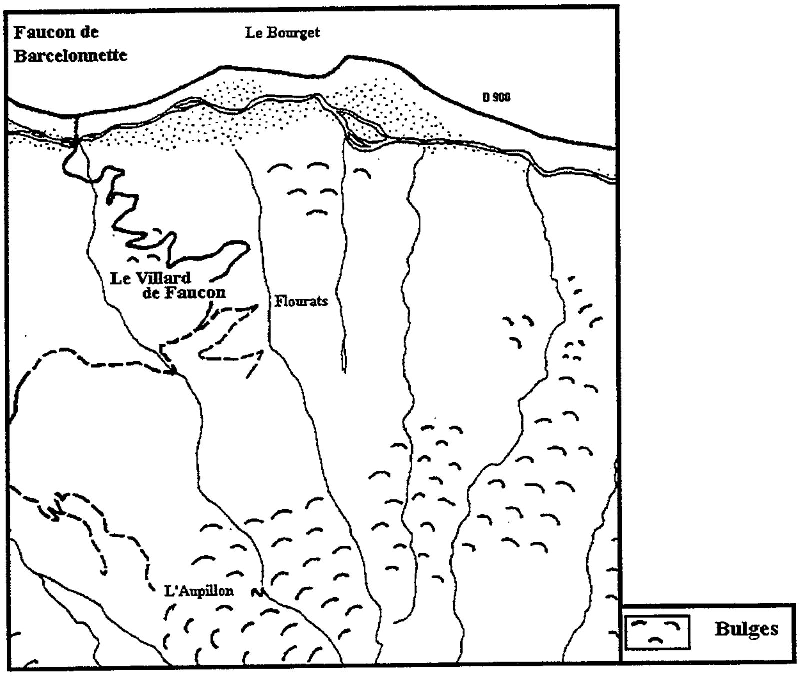


Fig 3b : Location of the hummocky terrains.

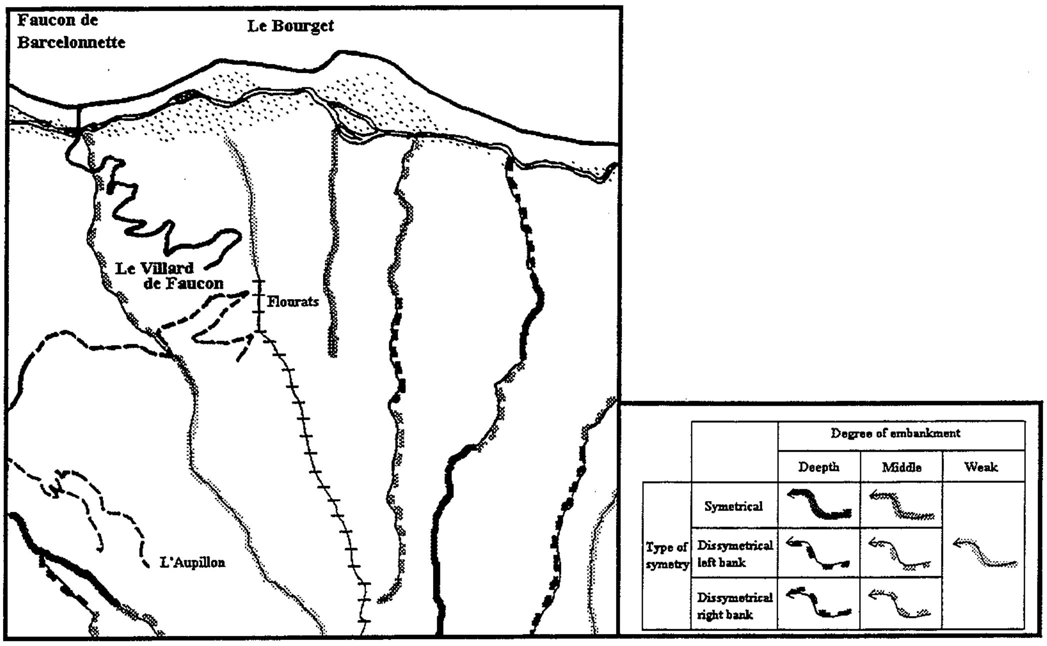


Fig 4a : Torrents embankment map.

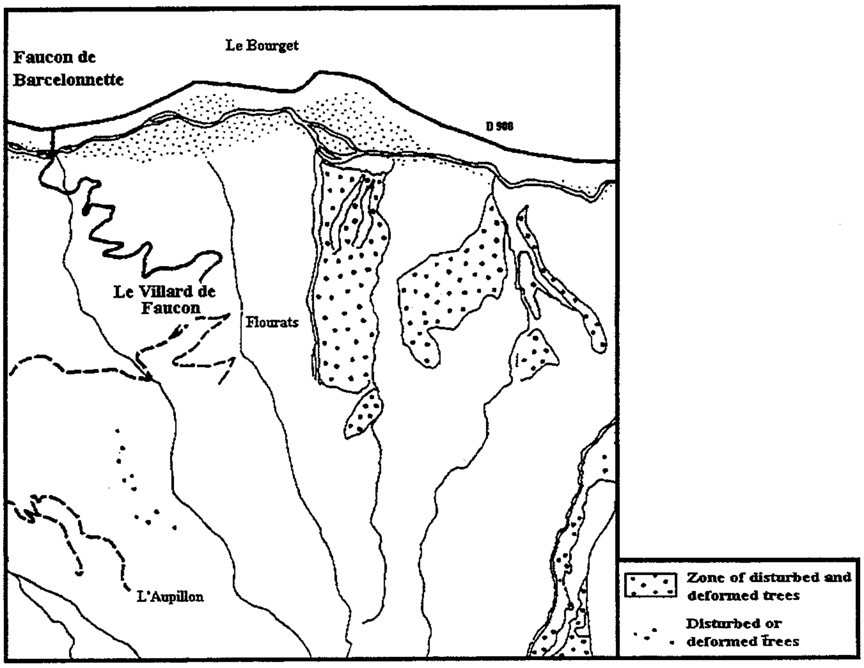


Fig 4b : Trees deformations map.

2°) Several geomorphological indicators are calculated from the limits outlined (inspired by Crozier's indicators) :

- uneven/total length of landslide
- width at the crown / width at the base
- width of the crown / total length of landslide
- width at the base / total length of landslide
- height of main escarpment / total length of landslide

These indicators are compared with the same indicators for the four active landslides mentioned earlier. In this way, we establish a degree of coincidence between indicators which reinforces the likelihood (or otherwise) of the location of an old landslide.

3°), We can then map the probable location of old landslides by comparison with the preceding map (Fig. 5).

2.3. Results

The results indicate :

- the presence of several large old landslides, almost comparable with the present active landslides,
- the presence of small slides of torrent embankment slopes, the outlines of which are more numerous and clearer; we will be able to judge their degree of activity when we return to the site,
- the presence of old landslides which apparently predated agricultural occupation of the site, but which have shown signs of reactivation since cultivation ceased and the flows were controlled.

III. RESEARCH INTO THE SHAPE AND GROWTH OF TREES

3.1. Landsliding cinematic established by observing the deformation of trees

In an active landslide, the direction and the degree to which trees incline can be used in combination with geomorphological observation to define the displacement mode of the land in which they are rooted. In addition, disturbances in tree growth provoked by earth movements directly affect the shape of the trunk between the base and the cime.

However, these deformations must be interpreted carefully, as they could be due to other causes, such as snow, wind, rain and temperature.

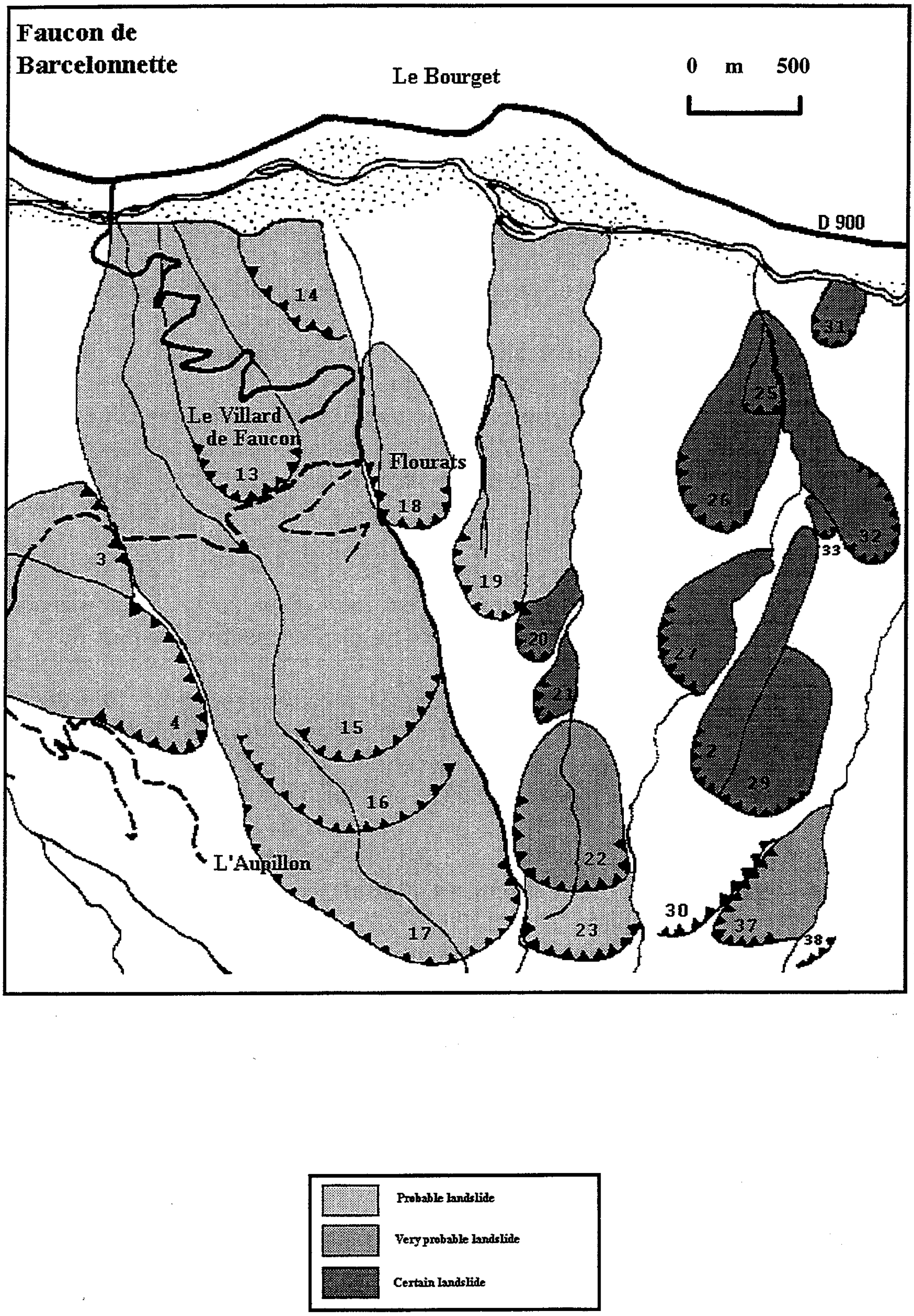


Fig 5 : Location and probability of landslides (final map).

3.1.1. Deformation of tree trunks and displacement modes

On the right flank of the large landslide at Poche, the superficial rooting of pines is sufficient to hold them firmly in the block of sliding earth; in this case we can establish the displacement mode from the inclination of the trunks (Fig. 6) and reconstitute the profile of the slope as it was before the landslide :

- a rotational movement running the length of the plane of a rupture and downstream of a shearing fissure. The base of the trunk leans downstream and the top leans upstream,

- a topple movement downstream of a traction fissure. The top of the tree leans upstream,

- pushing or burying by accumulation; the tree leans sharply downstream.

In some cases the inclination of the tree does not depend solely on the type of movement; it may be the result of denudation or a break in the root system, generally upstream of the tree trunk. This rupture is due to shearing along the rupture surface or a traction fissure. All the same, the inclination of the tree reflects the displacement mode, but exaggerates the effects (Fig. 7).

The inclination of around a hundred trees on the right flank of the Poche torrent was observed and analysed in order to establish a detailed map of the displacement modes (Fig. 8).

The map shows clearly the withdrawal, either in preparation or in progress, of the upper right flank predominantly by the numerous panneaux in rotational sliding on the one hand and the complexity of the development of the sliding mass below the downstream section of the right flank (opening and toppling of a panneau followed by a rotational or inverse movement).

3.1.2. Tree deformations and the development of displacement modes in time.

After inclination and if the land is stable, the tree progressively returns to vertical, above a more or less pronounced elbow. On the old landslides of the south slope at Barcelonnette some trees show several deformations. An inventory of deformed trees is being draw up in order to localise the morphology, the cinematic and the active and dormant years of these old landslides on a very detailed spatial scale by the known technique of measuring the dissemetry of growth rings.

3.2. Relationship between rainfall and the size of tree rings

Tree growth is directly connected with the environmental factors which govern the site on which they grow. The soil type, and in particular climatic conditions determine the way in which they develop. If external factors are favourable (good lighting, clement temperatures, regular rainfall and moderate winds) the trees flourish and their rings show considerable annual growth.

The Bois Noir forest (Pinus sylvestris L. and Pinus ucinata Ramond) is at an altitude of 1800 m . These trees are very hardy and adapt well to all types of environment, but, like other

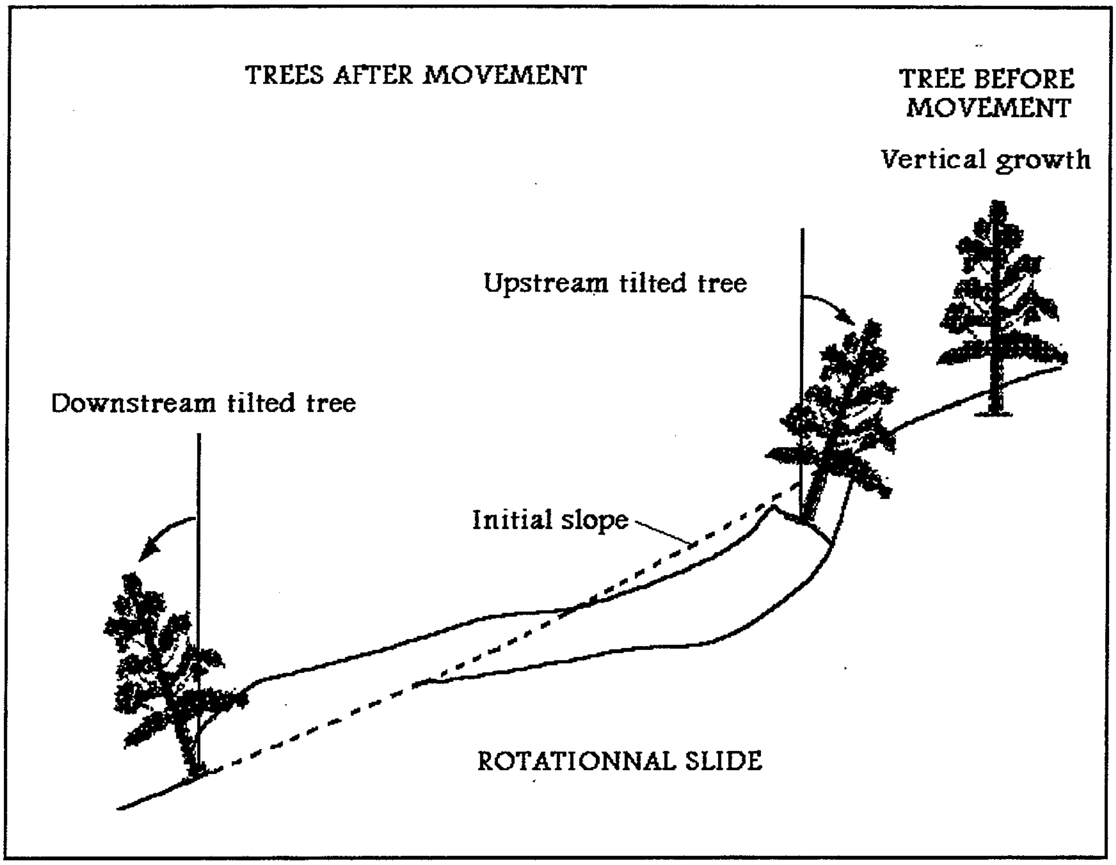


Fig. 6 : Inclination of the trunks on a rotational slide.

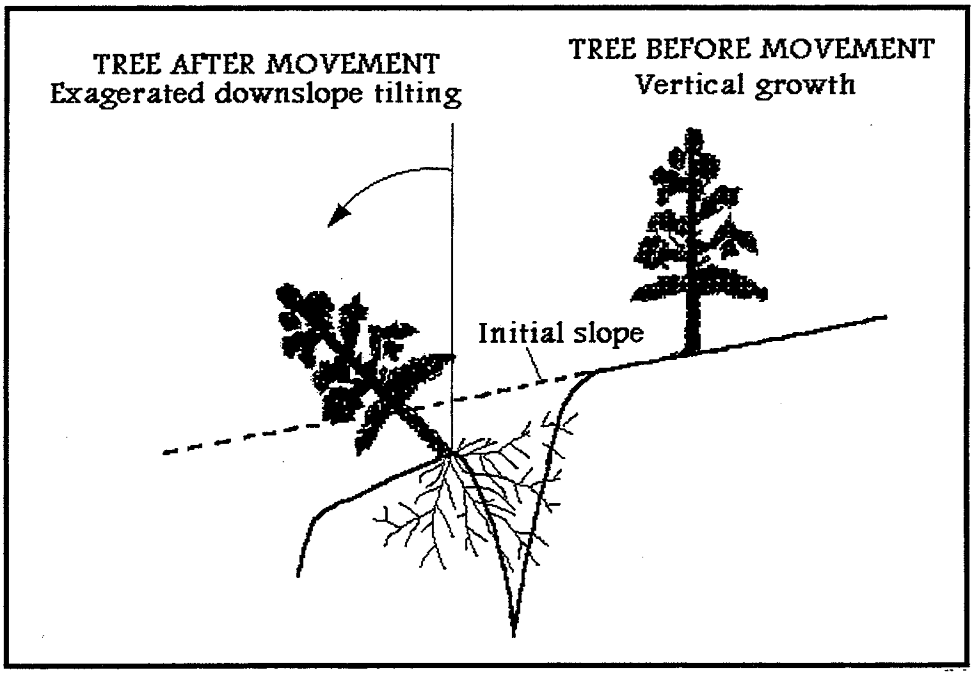


Fig. 7 : Exaggerated trees inclination in a topple movement.

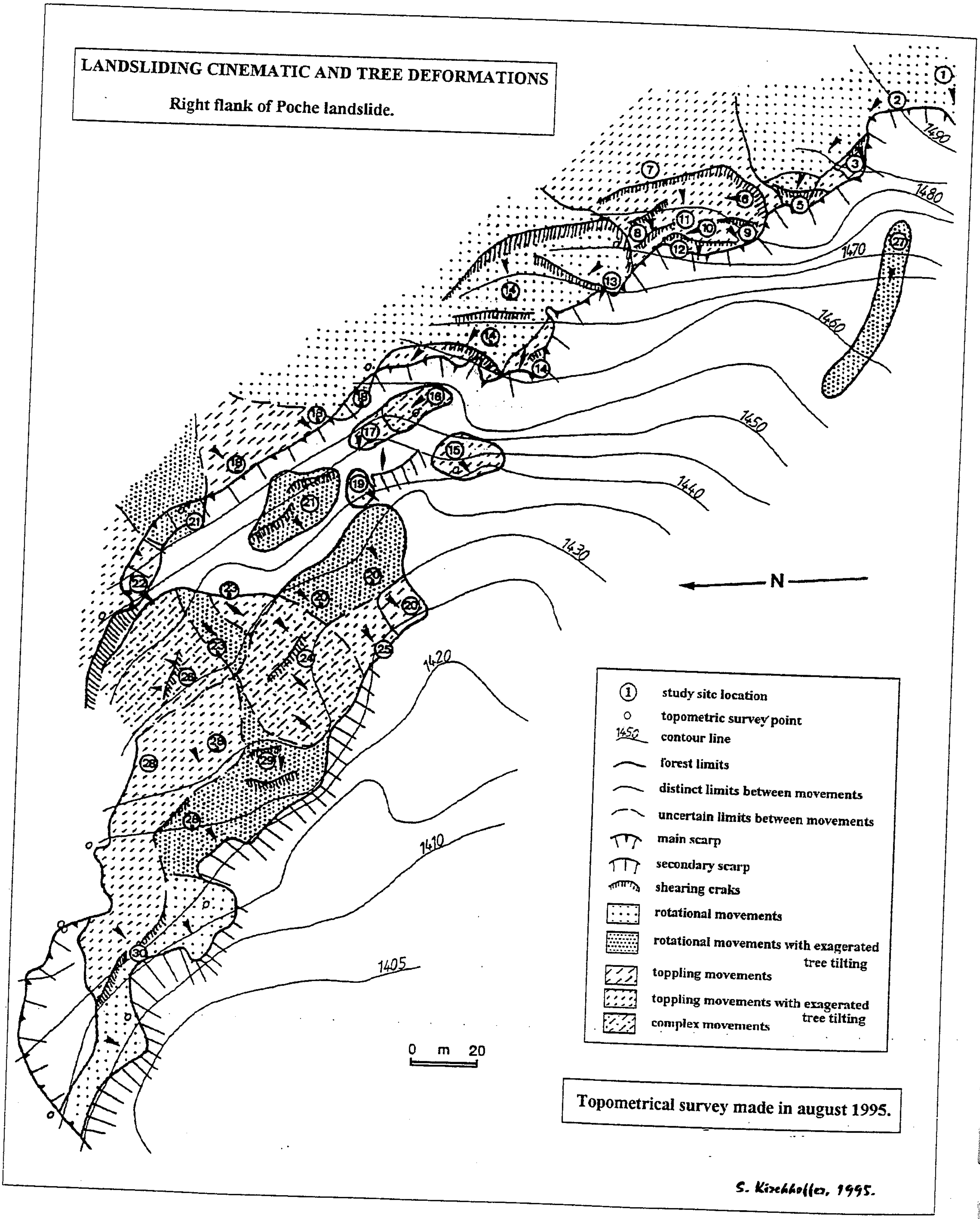


Fig. 8 : Landsliding cinematic and tree deformations on the Poche landslide.

strains, they are sensitive to fluctuations in rainfall and temperature; this seems to be a factor in limiting their growth.

3.2.1. Average annual ring width and annual rainfall

Rainfall data are incomplete for 1945, 1946, 1947 and 1953, and they were taken from those at Barcelonnette, at 1100 m, while the Bois Noir itself is at an altitude of 1800 m. This being so, the rainfall totals cannot be taken into account directly, and observations must be based on rising and falling trends.

Ring width and annual rainfall both diminished from 1944 to 1993, so there is a cause and effect relationship between the two (Fig. 9a). When trees begin to grow the rings are wide; they have more space and are not in competition with other plant populations; as time goes on competitive elements are established and the trees' growth diameter decreases.

Periods of strong growth (wide average annual ring growth) are usually associated with periods of heavy rainfall and the converse is also true. The years 1964 - 1973 are an example of this. The effect on the rings became apparent in 1971 and 1973 (very little ring growth inteed, less that 0,7 mm). The delay may be due to the cumulative effects of years of low rainfall.

From 1956 to 1958 the growth rate was considerable, reaching a maximum in 1958 but the maximum rainfall was late, peaking in 1960. In1961, furthermore, the growth rate was very low, though the preceding rainfall had been very high. From 1984 onward the rings were very thin for several years and growth increased only in 1993, whilst rainfall had been on the increase since 1991. This shows that there were other intervening factors - light, wind, temperatures, etc. The considerable decrease in ring widths is also due in part to the physiology of the trees themselves.

3.2.2. Average annual ring width and rainfall during the growth period of plants

In the mountains in the Barcelonnette basin growth commences in April and ends in September. The relationship between the average annual ring growth and the rainfall over the plant growth period (Fig. 9b) suddenly became closer; this was true for the rising trends from 1954 to 1958 and the falling trends from 1984 to 1988, as well as for exceptional years such as 1961 and 1984 (low growth rate) and 1947, 1957 and 1958 (high growth rate). However, this approach neglects the evaporation factor, which is associated with temperatures.

3.2.3. Conclusion

Dendroclimatology as applied to the Bois Noir at Jausiers confirms the close and direct relationship between the width of tree rings and rainfall during the plant growth period. Years of high and low rainfall were well reflected in the growth of trees. It should be recalled that in 1987 R. R. Bramm established the parallel between rainfall and the triggering of landslides in

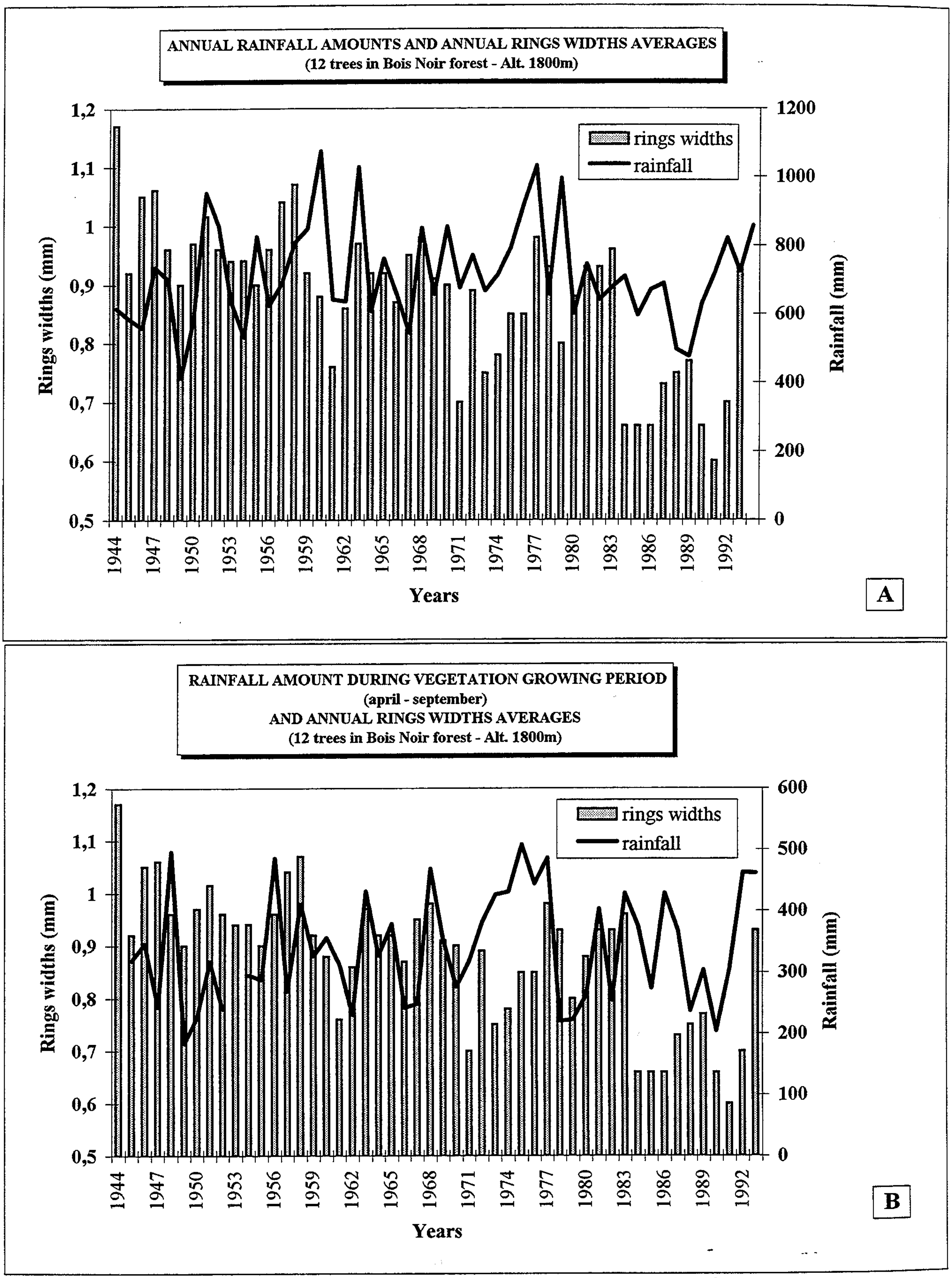


Fig. 9 : Relationship between rainfall and size of tree rings

the Riou Bourdoux sector (by calculating the tree ring eccentricity indicators and determining the frequency of onset or reactivation of movements in this sector).

IV. THE COLLECTION OF DATA ON HISTORICAL GEOMORPHOLOGICAL ACTIVITY BY ARCHIVE INVESTIGATIONS

4.1. General

4.1.1. Examination of various archive documents

This has enabled us to establish an inventory of the various hazards which have occurred since 1850 in the six communes of the Barcelonnette basin.

Various sources of information were consulted. Administrative documents such as expert reports, statements, technical notices, deliberations and local decrees are archived by series and files. The second group consists of local and regional newspapers, in which natural hazards are usually covered under a general news heading.

The maximum of information about the incident is recorded from each source on a prepared data sheet. The database can then be consulted in several ways, depending on the information required, using a specifically designed consultation method.

This work involved visits to Digne, the site of the Departmental Records of the Alpes de Haute-Provence and various Departmental Offices such as Agriculture and Equipment, the ONF (Office National des Forêts-National Forestry Office) and the RTM (Service de Restauration des Terrains de Montagne-Mountain Land Restoration Service), to Barcelonnette, the Town Halls in the various communes in the basin in order to consult the Minutes of Council meetings and other local administrative documents. The Barcelonnette division of the ONF also had many records which were relevant to the subjects studied, including a very interesting and instructive collection of old photographs, accurately dated.

The investigation enabled us to establish a data bank of 958 references arising since 1850 in the five following categories :

- **Climatic**	: storm, hail, drought, gales,
- **Torrential flowing**	: overflows and inundations, floods, debris flows, gullying,
- **Landslides**	: landslips, rockfalls, mudflows,
- **Snow avalanches**	
- **Earthquakes**	

The torrential flow risk is the best represented (fig. 10) being 60 % of all the references listed, while earthquakes represent only 5%. The frequent occurrence of this risk is not surprising in an enclosed basin drained by a large number of torrents, often swelled by the heavy and sometimes violent rains characteristic of the mountain-Mediterranean climate and by melting snows from the high peaks surrounding it.

The large number of incidents listed must nevertheless be diminished. In fact, the same phenomenon may be listed in several communes. For example, the landslip at Valette is often recorded both at Barcelonnette and St. Pons. Furthermore, since its onset in 1982 further reports and press articles have swelled the list of references as the landslip developed or work was carried out on it. For this site alone we have 21 different references in the databank. A further example is the flood at Ubaye in May 1856, a single incident at regional level, which is nevertheless recorded in all the communes where it caused damage. This is also the case for the flood of June 1957. Finally, the archives may vary in their reports of the incident and the information may be inaccurate, making it difficult or even impossible to establish the facts.

4.1.2. Accuracy problems

In the second instance we were able to exclude seismic risks and climatic disasters, of which there were few examples, and avalanches, a special case and better known.

- We have therefore chosen to analyse the distribution in space and time of **two risk categories**, i.e. « Landslides», comprising landslips, rockfalls and block falls, mudflows and «Torrential flowing », which includes torrential floods, overflows and inundations, debris flows, gulleying. Of the 701 remaining incidents, 580 (83 %), were torrential flows and only 121 (17 %) were landslides.

- **Landslides** : Apart from the accurate descriptions in technical reports, these were often described by non-specialists; this is particularly true for incidents reported in the press. As a result the morphological term used and the actual description in the article were sometimes confused. Wherever this occurred we corrected it and attributed the term which seemed to us most appropriate.

- **Incidents :** They are all placed together regardless of size, extent and depth, but this is of no consequence, as in the immediate future we are only seeking to establish the situation or climatic conditions prevailing at the time of onset. In any event, they are all obviously significant, otherwise they would not have been mentioned in the various archives.

- **Torrential flows :** The six cases of overflows reported have been included with the inundations. Fifteen references to floods are also associated with other phenomena (debris flows, overflows or inundations) and we were unable to make an accurate assessment of their relative importance from the descriptions.

4.1.3. Critique of information

This is essential, as the chronological series can be misleading in a way. In fact the number of incidents may sometimes be:

- **amplified**, following a major disaster, public interest is such that even minor incidents are reported.

- **underestimated**, where phenomena affect land which has been abandoned or unused because of rural decline, where there has been no damage to infrastructures (pipeline systems, communications networks etc.). The Valette landslide in the Barcelonnette commune provides a good example. It was started by a rock fall at an altitude of 2000 m in March (?) 1982 but there was no mention of it in the press until 1988 when further developments (the onset of a mudflow in the La Valette torrent) gave rise to fears for the built-up site at the mouth. It should be said, however, that this landslide was « monitored » by the authorities - surveys and works were carried out periodically from 1982 onward (Evin M. 1990; Colas G. and Locat J., 1993). A further example is the Bois Noir landslide at the Jausiers commune, which apparently occurred in the spring of 1993. It is not mentioned in the records because it only affected one wooded slope and a forest footpath which ended, without issue, in abandoned grassland.

4.1.4. Results

The distribution of landslides is as follows (Fig. 11) : The movements observed most frequently are landslides (63 % of the total), followed by rock falls and block falls (26 %) and mudflows.

Floods are more numerous in torrential flowing (Fig. 12) with 428 references (73 %), followed by debris flows (13 %), inundations (12 %) and gulleying only 2 %. Floods combined with either debris flows or inundations account for only 15 references which include floods.

4.2. Occurrence of hazards

4.2.1. Annual occurrence

Figures 13 and 14 show the number of references recorded annually for each hazard in the form of an histogram and the curve for accumulated references; they give a clear demonstration of the characteristic periods as a function of the slope on the right.

For the torrential flowing, three characteristic periods can be distinguished (Fig. 13) :

- **Until 1914 :** there are a great many floods and debris flows from 1850 to 1887, either because of deforestation in the land in the basin (floods of May 1856 and 1863) or because the beneficial effects of corrective works were not yet evident (floods of 1868 and 1876). Corrective works began in 1864 with the law on reforestation and returfing (acquisition of 11 000 hectares of land, reforestation over 25 000 hectares, construction of several hundred barriers of all sizes, road resurfacing, drainage etc.). The benefits of these corrective works began to be felt after 1887 and debris flows tend to disappear from then on.

- **1915-1949 :** an obvious fall in the number of debris flow incidents is due to works carried out, particularly during the twenty years from 1929 to 1948, but the works deteriorated and were not maintained. However, we should note the incidents in 1926.

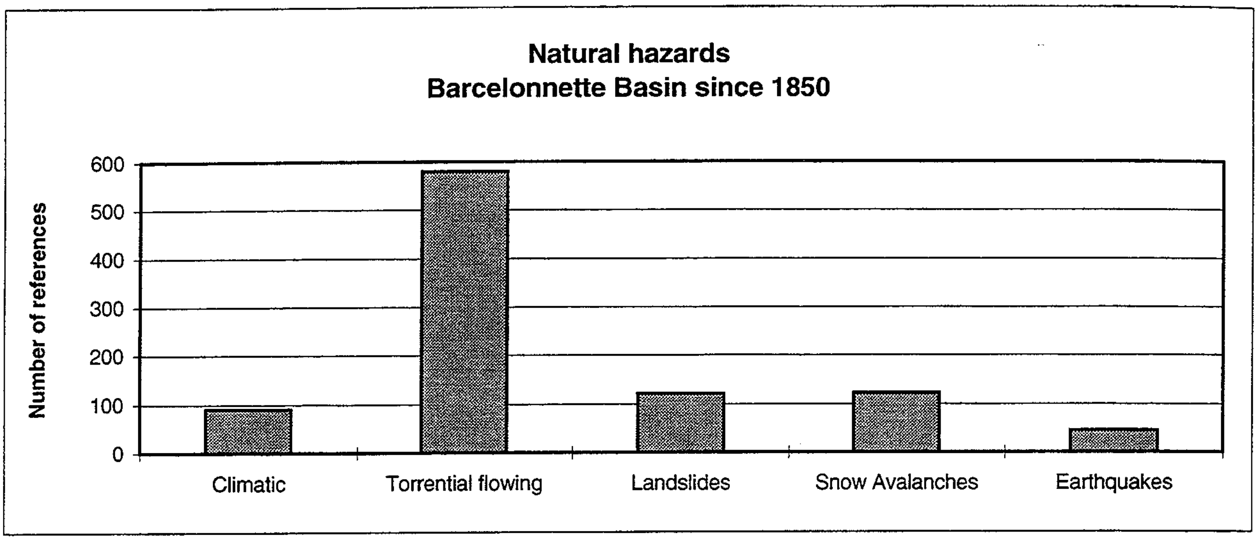


Fig. 10 : Natural hazards in the Barcelonnette Basin since 1850

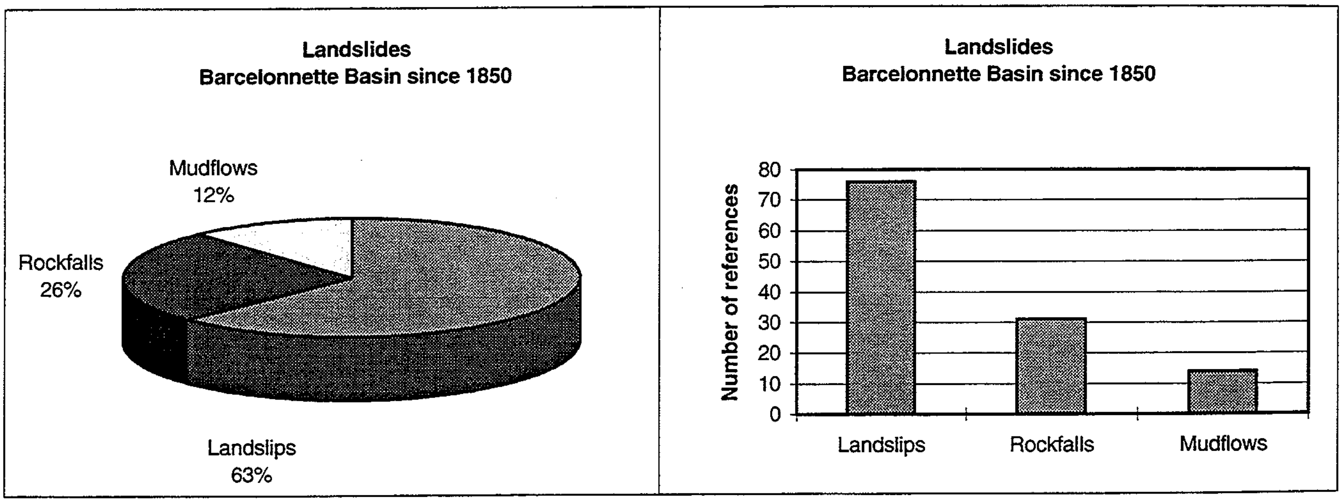


Fig. 11 : Distribution of landslides in the Barcelonnette Basin since 1850

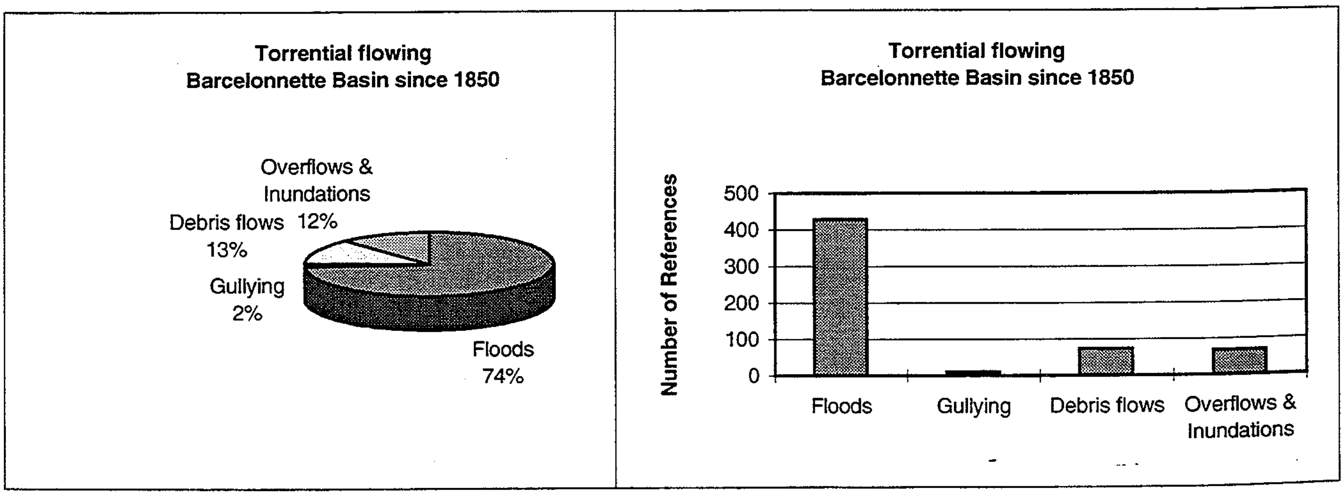
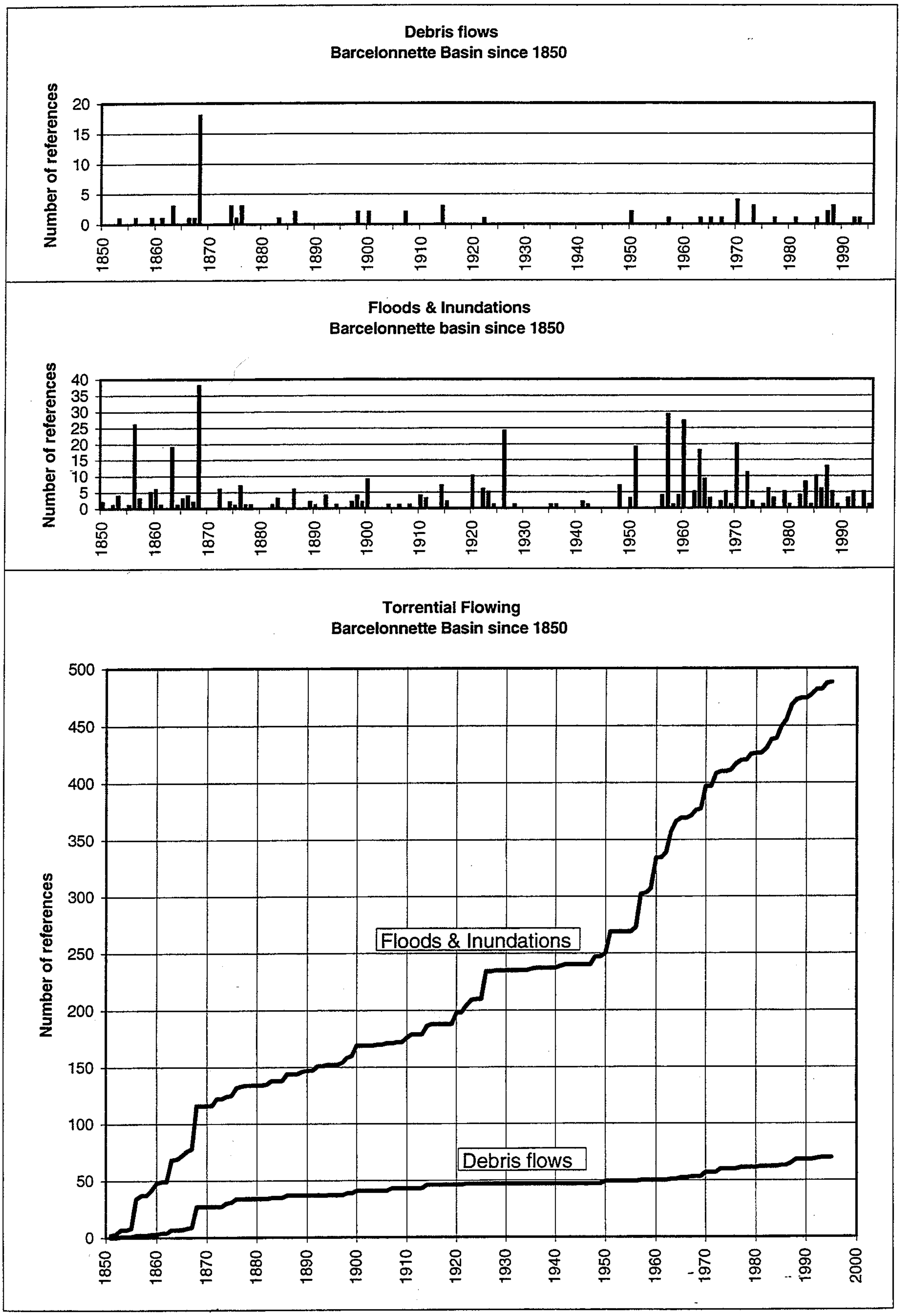


Fig. 12 : Distribution of torrential flowing in the Barcelonnette Basin since 1850



Debris flows
Barcelonnette Basin since 1850

Floods & Inundations
Barcelonnette basin since 1850

Torrential Flowing
Barcelonnette Basin since 1850

Fig. 13 : Annual occurrence of the torrential flowing

- **1950-1990 :** an increase in hazards arises largely from the decrepitude of the works, requiring a complete reorganisation of the corrective systems (Riou Chanal, Riou Bourdoux). In particular we note the centennial flood of the Ubaye in June 1957, but there are others in 1951, 1960, 1963, 1970 and 1987.

The distribution of landslides (Fig. 14) is fairly regular during these periods; however, there is a « rise » in the number of incidents at the beginning of the 1980s which should be connected with the numerous reactivations and extensions of the La Valette landslide, and may arise from the greater attention paid to these phenomena which we mentioned earlier.

4.2.2. Seasonal and monthly distribution

It is important to state at the outset that this analysis was possible because of the relative accuracy of the information regarding the onset dates for these phenomena. For the torrential flow hazard (Fig. 15a) the day or month is known in 77 % of cases and only 4 % are undated. Dates for the landslide hazard are less precise (Fig. 15b); only 66 of the 121 references, i.e. 55 %, can be dated to the nearest month or season.

- **Occurrence of landslides**

Landslides can occur at any time of the year (Fig. 16a); however, there is a contrast in the monthly distribution - no movement is recorded in December and only a few in April, October and November. The greatest number are recorded in May, August and September. This is seen in the following seasonal division (Figs. 16b): 35 % occur in spring, as compared with only 14 % in autumn. The majority of mudflow incidents occur in the summer months in conjunction with the intense stormy rains, which corresponds quite well with observations of this type of phenomenon elsewhere, for example in the High Alps (Fanthou T. and Kaiser B., 1990).

- **Occurrence of torrential flowing**

Floods and inundations are observed from May to November, peaking in July (Fig. 17a). Forty-seven per cent of these incidents occur in summer (Figs. 17b). This distribution is usually to be found in mountainous areas. Spring floods arise from excess rainwater combined with the nival melting snows. Summer floods are due to violent localised storms. Autumn floods are often dangerous, as they arise from periods of very heavy rainfall (C.f. later).

4.3. Distribution in space

4.3.1. Landslides

These hazards affect all the communes, both on the shady and sunny sides of the mountain. The greater majority are canalised in the small valleys (Poche, Supersauze etc.) but they can also undermine the banks of streams and affect the trenching of road infrastructures, etc.

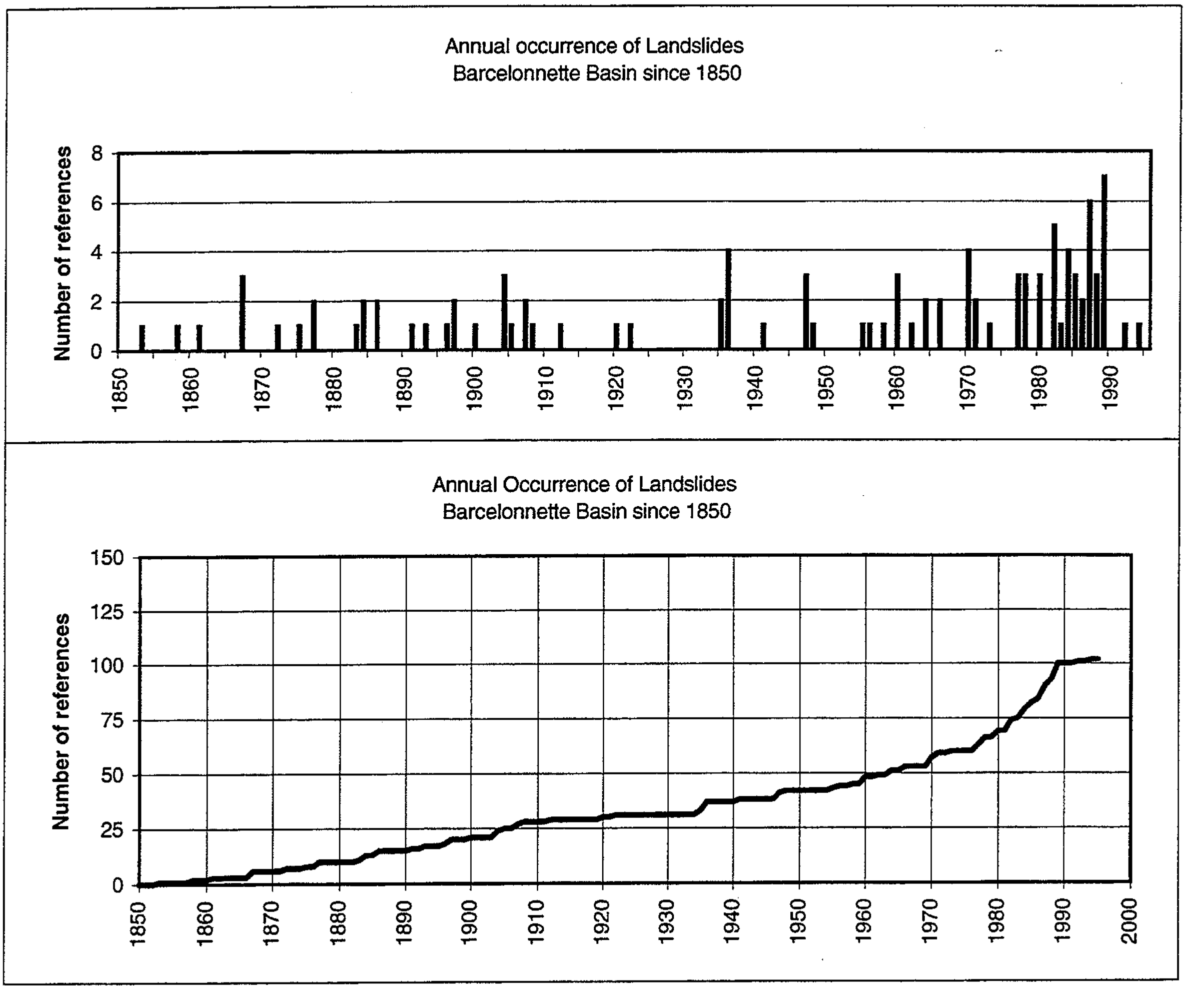


Fig. 14 : Annual Occurrence of the Landslides

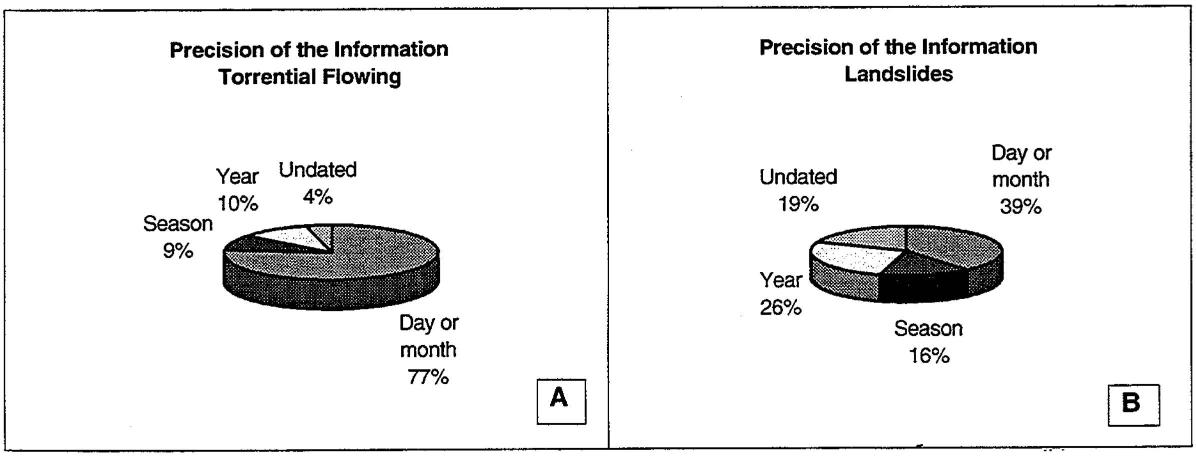


Fig. 15 : Precision of the Information in the Barcelonnette basin since 1850

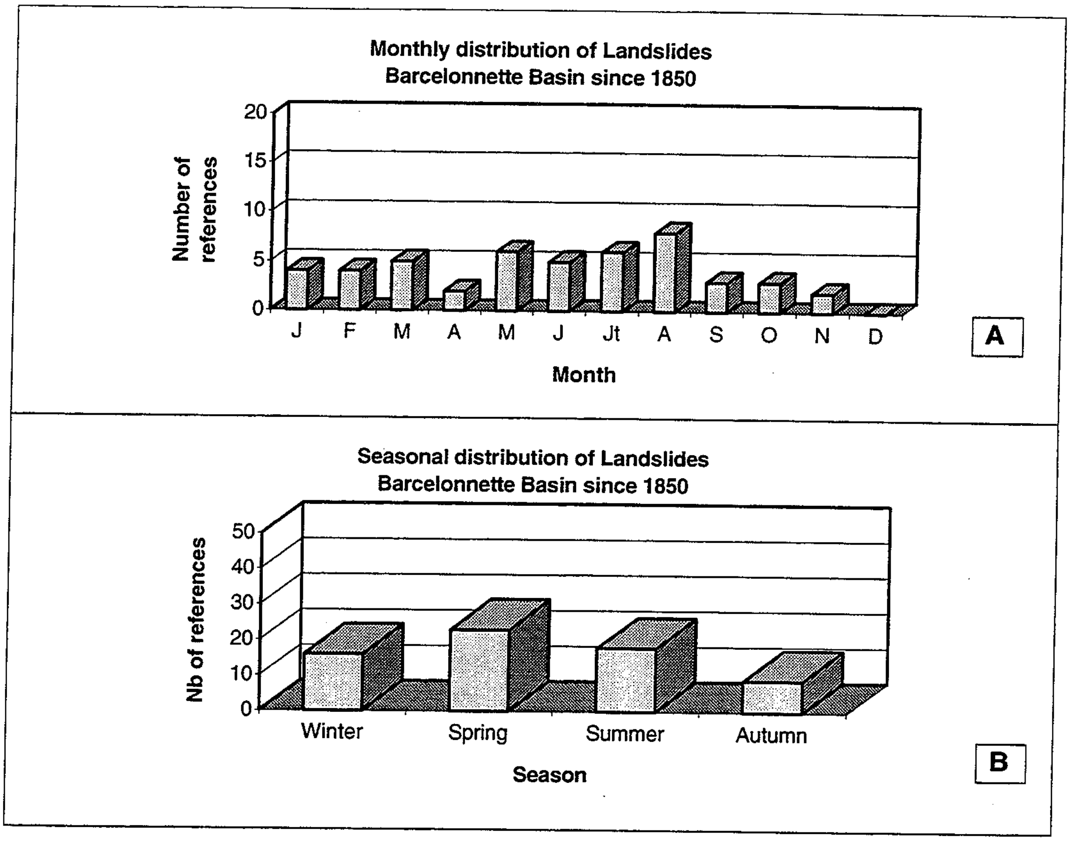


Fig. 16 : Occurrence of landslides : Monthly and seasonal distribution

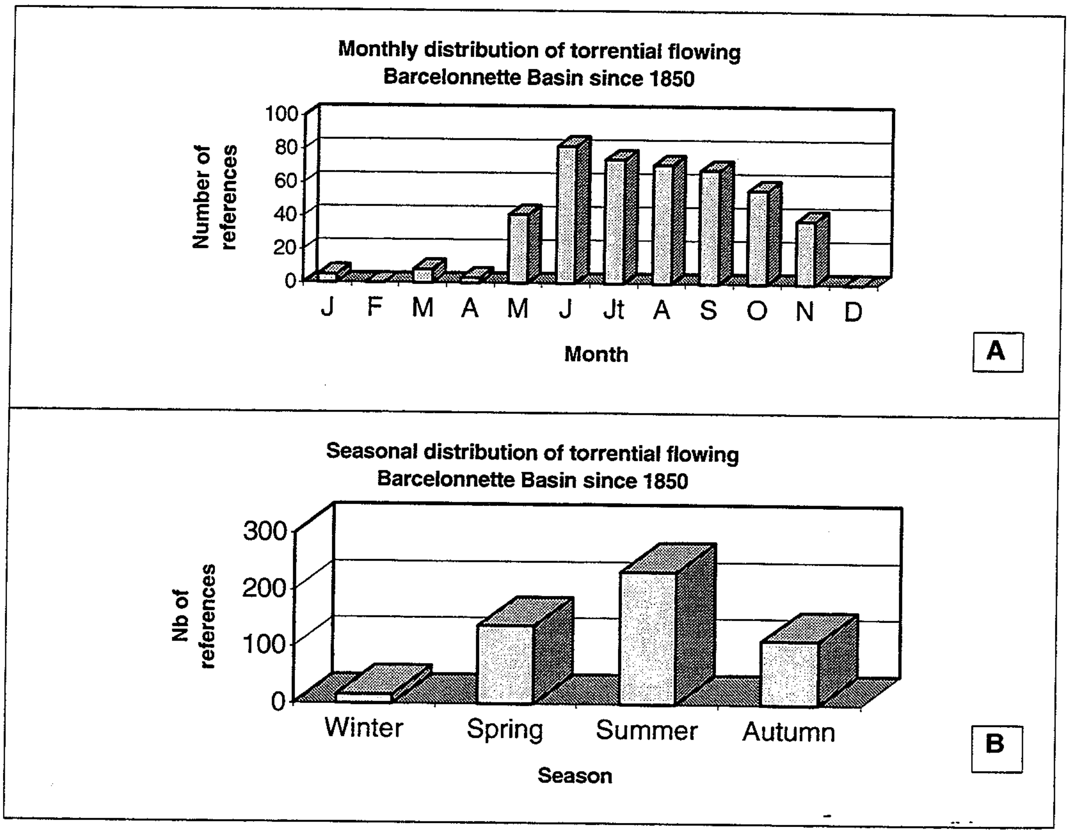


Fig. 17 : Occurrence of torrential flowing : Monthly and seasonal distribution

4.3.2. Floods

Flooding affects all the communes because of the many streams in a relatively limited area flowing into the Ubaye, which irrigates the communes of Barcelonnette, Jausiers, Saint Pons and Enchastrayes.

4.3.3. Debris flows

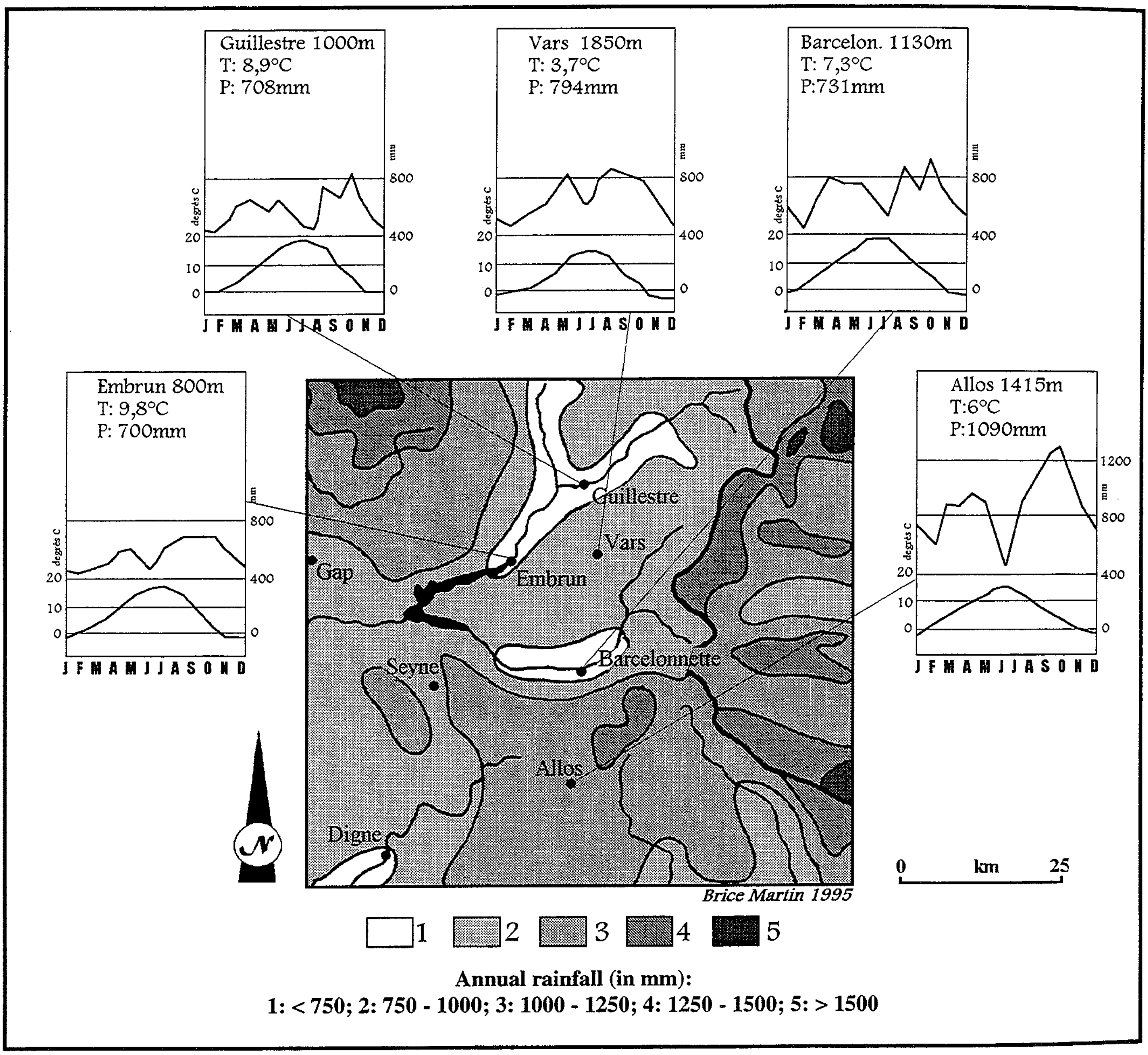
These phenomena occur in some communes more often than in others. Saint Pons and Faucon, for example, are significantly affected, unlike Thuiles, where incidents are relatively rare. This is explained by the fact that the land around the Ubaye is well wooded and retains materials which prevent the formation of debris flows. Generally speaking, we observe that debris flows usually occur on the right bank of the Ubaye. The maximal sunshine on the sunny side encouraged the building of villages but over the centuries this has involved the clearing of land and erosion has recommenced. Today the forest is regaining ground, spontaneously or artificially. The shady side has always been the domain of forests and mountain pastures.

V. RAINFALL HISTORY IN THE BARCELONNETTE BASIN

5.1. Climatic caractéristics of the Barcelonnette region

The Barcelonnette basin occupies a special position in the region, as the Moyenne-Ubaye is a relatively dry mountain sector with a rainfall average of 730 mm for the period from 1954 to 1994 at the Barcelonnette station (1140m), and 678 mm at the Jausiers post (1510m) for 1961 to 1994 (Fig. 18). Although the Jausiers station is higher than Barcelonnette (Fig. 19), it is sheltered by the basin, with a normal rainfall lower by 6.5 % than that of Barcelonnette. The explanation doubtless lies in the overall topographic configuration of the valley; the Jausiers station is between the South-North axis of the valley descending from the Restefond col, while Barcelonnette is enfolded between the two sloping flanks of the Ubaye in an east-west direction. The two stations are undeniably subject to different climatic influences.

The basin's pluviometric regime seems to be subject to both continental and mediterranean influences, with an autumn maximum and a strong inter-annual variability (1075 mm in 1960 and a minimum of 413 mm in 1949), a winter minimum, a regular secondary spring maximum and a secondary summer minimum which may be punctuated by intense storms. The main maximum is in October, with a secondary maximum for May. Two minimal figures characterize February and July.



Brice Martin 1995

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Annual rainfall (in mm):
1: < 750; 2: 750 - 1000; 3: 1000 - 1250; 4: 1250 - 1500; 5: > 1500

Fig. 18 : annual rainfall and ombrothermic diagrams
(upper curve: monthly rainfall; lower curve: monthly temperatures).

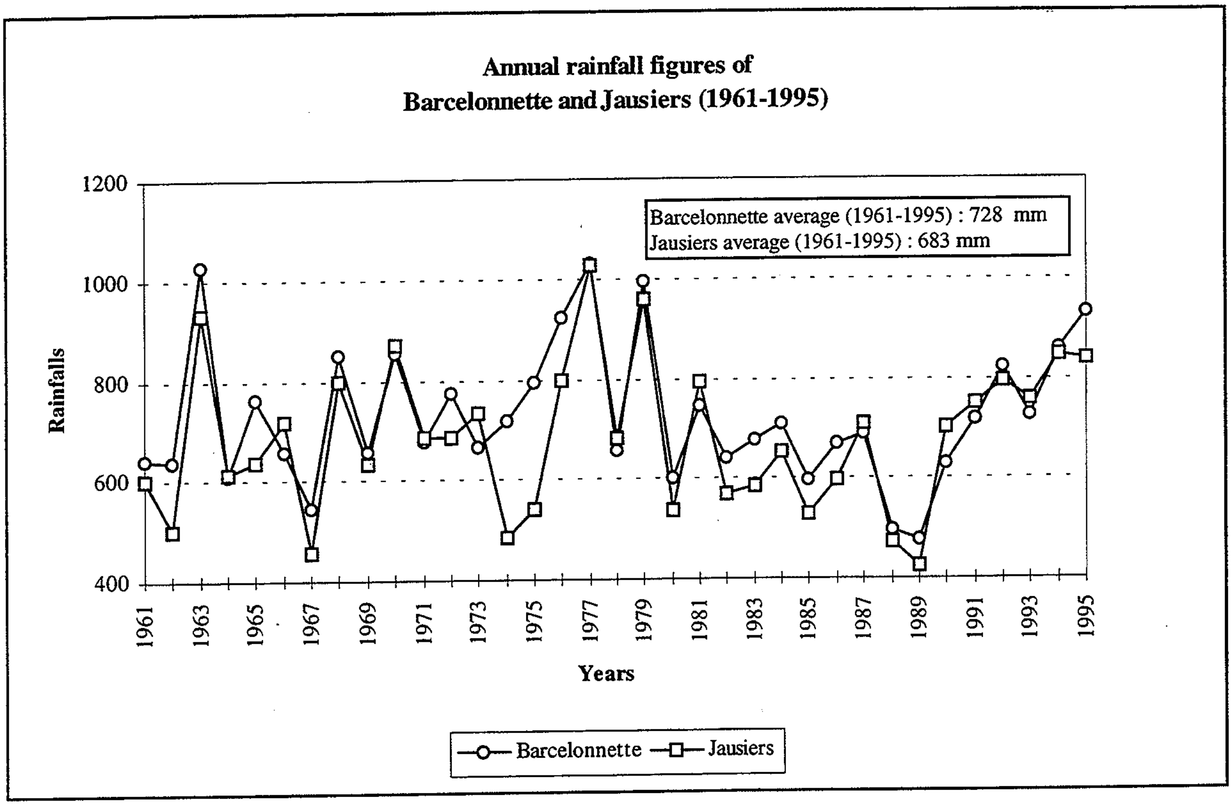

Fig. 19 : Annual rainfall in Barcelonnette and Jausiers between 1961 and 1995. (Météo-France data)

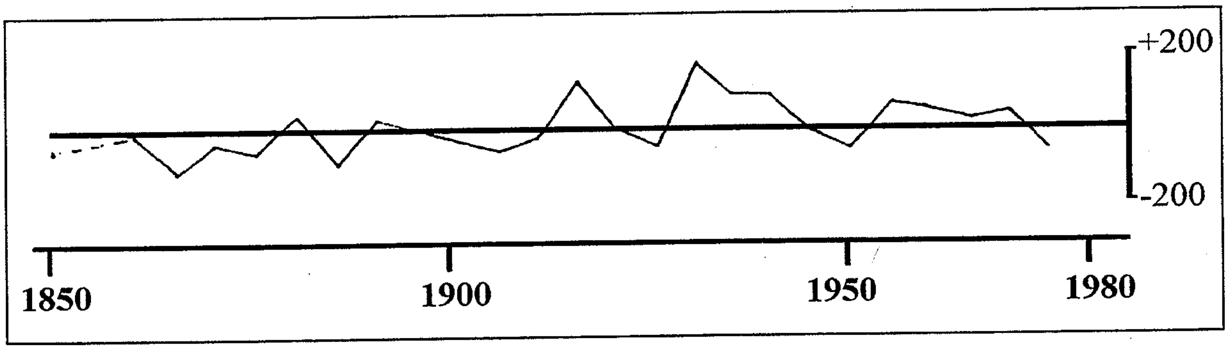

Fig. 20 : Annual rainfall in Gap (difference with the average).

5.2. Available data

In the Barcelonnette and Haute-Ubaye basins the data on climatic development vary considerably with the period of reference.

Prior to1928, the information is largely qualitative and indirect as it is deduced from explicit factors such as tree cernes, glacial fluctuations, agricultural production and profitability etc. However, the development is occasionally specified directly by information from old climatic series but these are either at some distance from the zone studied (Gap station) or irregular and unreliable (annual rainfall in Barcelonnette from 1900 to 1928, calculated by Bénévent's sliding averages).

From 1928 onward : we have recorded computerized data

- from 1928 to 1961, from the Météofrance station at Barcelonnette, the missing data being extrapolated from those at Vars. The two stations are linked statistically because the correlation coefficient for monthly rainfall is 0,82.
- from 1961 to 1996, from the Météofrance stations at Barcelonnette (1140m) and Jausiers (1510m), 8 km. apart. Additional information has occasionally been obtained from computerized data from the stations at Orres and St. Paul (12 km. and 16 km. away), which are also linked statistically (correlation coefficients between 0,83 and 0,88).
- since 1st September 1994 by a self-registering raingauge installed in the context of TESLEC Program at La Rente (Enchastrayes; altitude 1680 m), immediately next to the Super-Sauze landslide, 7 km. from the Jausiers post and 5 km from Barcelonnette. This apparatus provides continuous readings (precipitations), supplementing Météo-France's daily data.

We must therefore be prudent in comparing the various periods with a view to retracing the general development. The first period is more indicative of annual or pluriannual trends.

5.3. Results

5.3.1. Climatic development from 1860 to 1928

A great deal of data from the archives has enabled us to show several reliable and highly individualised climatic successions.

- **from 1860 to 1886** : 1860-1870 was a particularly dry period culminating in the course of the episode extending from the spring of 1861 to the autumn of 1862, in accordance with the rainfall recorded at Gap (Fig. 20). Thereafter we enter a period of high humidity but with considerable seasonal variations, as we note several successions of dry years followed by wet years prevailing until the beginning of the 1880s (1881: a great deal of snow in winter, then no rainfall at all from mid May to September). The readings at Gap indicate a progressive increase in rainfall up to 1880. Thus we note 989 mm in 1877 and 1152 mm in 1878, in spite of a dry winter (the present annual average is 700 mm).

- **1886 to 1898** : After a final rather cold, wet year (937 mm at Embrun) the situation changes once more and we see a remarkable succession of cold, dry years from 1887 to 1898, marked by low rainfall at Embrun (1892 : 619 mm; 1894: 552 mm; 1897 : 578 mm) with marked minima on the climatic series at Gap. Only in 1895 and 1896 were the totals higher, in spite of winters with little snow (a total of 23 mm for January, February and March 1896), summer storms and very wet autumns (1021 mm at Gap, 318 mm being for October alone).

- **1899 to 1916** : The period of drought at the end of the 19th century continued at the beginning of the 20th century but this time it proved to be associated with a significant warming. After 1905 we enter a new wet, cool period (1307 mm at Barcelonnette in 1907), with heavy snowfalls and a succession of « rotten » summers until 1916-1917. At Barcelonnette, sliding averages over 5 years indicate a decrease in rainfall until 1910, followed by a rise until 1917, but with many incomplete years, which entail an underestimate of real rainfall.

- **1917 to 1928** : A phase of diminished rainfall marked in particular by winter deficits continues until the mid-1920s and recurs in 1929. Rainfall at Gap shows a similar trend. A relatively dry period between 1917 and 1924 is followed by a progressive rise in rainfall (the year 1927 was very wet: 1237 mm at Barcelonnette).

5.3.2. Development since 1928

The analysis of rainfall development is based on the 5-year sliding average curve covering the whole of the 20th century for the Barcelonnette station. Rainfall development at neighbouring stations over shorter periods matches that at Barcelonnette.

The five year sliding average curve (Fig. 21) has been calculated for the period from 1928 to 1995 using annual rainfall figures from the Barcelonnette post. The missing values from 1928 to 1953 have been extrapolated from the Vars station. Bénévent presents a curve of the same type in Péguy's work (Péguy, 1947) for the earlier period from 1900 to 1941, but the annual figures used to determine it contain many errors, as Bénévent has taken account of the rainfall figures for the incomplete years, involving an under-estimate of his 5-year sliding averages. Unfortunately, this had already occurred during the period from 1900 to 1941. From 1961-1994, the correlation rates between the monthly figures for the Barcelonnette and Jausiers stations vary from 0,78 to 0,98. These coefficients enable us to calculate good extrapolated values to compensate for the lack of data from one or other of these stations during this period.

On the 5-years sliding average curves, the successive periods of heavy and light rainfall show a complex undulating phenomenon :

- the "major cycles" comprise extremely long wave oscillations (35 - 40 years), with a high amplitude of 300 to 350 mm.;
- the "intermediate cycles" comprise secondary oscillations of 15 to 20 years in length, with a lower amplitude of the order of 150 to 200 mm.;

- variations of low amplitude (around 50 mm) over a maximum of one, two or even three years give rise to inversions of tendency during ascending or descending phases defined by major pulsations.

Over the century as a whole, therefore, a fairly regular "cyclic" development is discernible, with no particular general tendency to high or low.

In detail, therefore, we find relatively dry years at the beginning of the 1920s, followed by increasingly wet years from 1928 to 1937; there is a period of decreasing rainfall from 1940 to 1950, after which year it increases once more until the beginning of the 1960s.

Thereafter rainfall diminishes until 1970, then increases continually during the decade from 1970 to 1980, when a further fall commences; the values were nevertheless higher than average until 1987. Then we find a period of four years with very little rainfall (clearly visible on the sliding averages over two years), in sharp contrast with the succession of wet years from 1991 onward. We find many individual years of exceptional rainfall (1935, 1951, 1960, 1963, 1977) and more rarely pluriannual sequences of very wet years : 1958-1960, 1976-1979 and in particular 1992-1995.

Information regarding temperatures was limited in the past and the approach proved more difficult because we had to take account of data from Vars, Barcelonnette and St. Paul successively. Earlier series show progressive global warming throughout the 20th century, with cooler periods during the 1930s and between 1960 and 1980, and warmer periods in the decades from 1950 to 1960 and 1980/1990.

VI. RELATIONSHIP BETWEEN LANDSLIDES AND CLIMATE PARAMETERS

6.1. Rainfall and the number of movements recorded (first triggering or reactivated)

The relationship between rainfall and the recorded movements have been analysed qualitatively on an annual or monthly scale, in the form of a simultaneous representation in accordance with variable «step-time». It should be recalled that for the period from 1900 to 1953 we only knew the annual rainfall figures, indirectly or by extrapolation, and the monthly rainfall series are only complete and reliable from 1954 onward.

6.1.1. Annual rainfall : 1900-1994

Some wet years and certain periods of excessive rainfall (Fig. 22) are also years in which movements are numerous, for example 1907, 1926, 1935, 1960, 1977, 1959-1965 and 1975-1981. On the other hand, there are periods of one or several years of particularly low rainfall which show many movements, 1904, 1920, 1964, 1947-1948 and 1982-1990 being examples. However, it should be noted that many references relate solely to the Valette site.

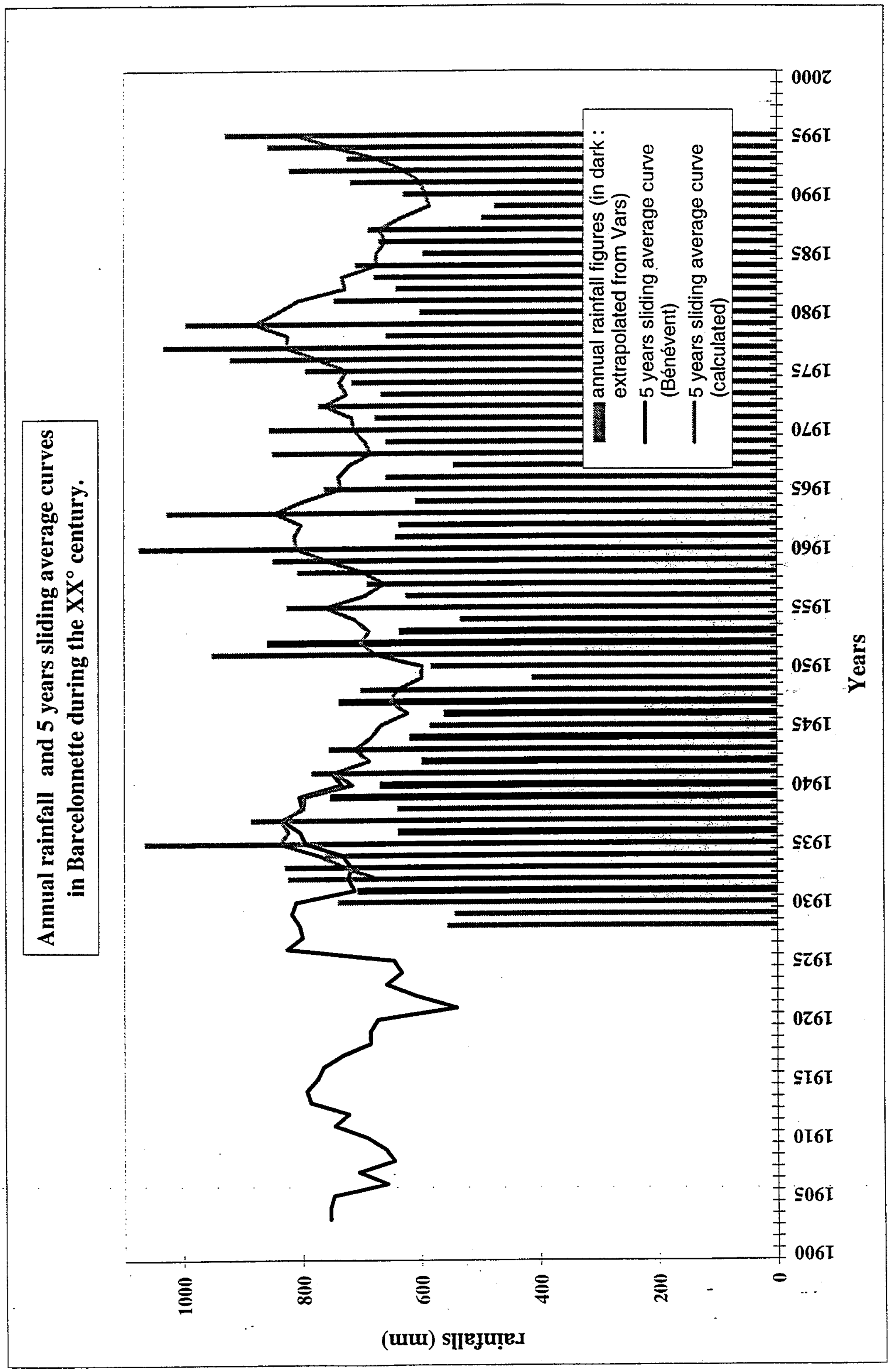

Fig. 21 : Rainfall evolution in Barcelonnette during the XX° century.

6.1.2. Monthly rainfall : 1954-1994

There is also no real correlation on the monthly scale (Fig. 23), even if some cases are associated with heavy rainfall in the preceding month or months, for example October 1977, the winter of 1978, June 1983 or October 1960. Most movements are dated by the month and the day is not specified, so it is not useful to analyse daily or decadal rainfall.

6.2. The role of climatic conditions in the triggering of a movement : the Valette landslide

The landslide at La Valette occurred in March 1982. A rockfall disorganised and overloaded the land beneath it (Combes F., 1990; Evin M., 1990; Colas G. and Locat J. 1993). Six years later in January 1988 the landslide descended as far as the road linking the farms if La Valette and Serre, the date on which a mudflow commenced and extended over a distance of some 500 m at an altitude of 1400 m to 1200 m, with a volume of the order of 50 000 m^3. The total volume destabilised in January 1988 was estimated at some 6 million m^3. The surfaces disorganised were 26 hectares in 1983, 32 hectares in 1984 and 50 hectares in 1985.

The prevailing climatic conditions and the dates on which the incidents became apparent are mentioned briefly. Some authors, however, give the date as **March 1982**. G. Colas and J. Locat (1993) indicate that « the movement started when the snow began to melt in March 1982 after heavy rainfall on a mantle of snow ». It would be interesting to confirm this.

6.2.1. The data available

Daily rainfall and temperatures are available from 1954 onward for the Barcelonnette station (at an altitude of 1140 m). There is no data for the whole of 1982. The Jausiers station (at an altitude of 1510 m, 8 km to the east) provides data on daily rainfall from 1961 onward. The missing rainfall data have been reconstituted using monthly totals, by a simple linear correlation beween the Barcelonnette and Jausiers stations. The correlation coefficients vary from 0,78 for the months of August and February to 0,98 for October.

In the absence of temperature data for 1982 in the Barcelonnette basin we have used figures from the St. Paul station in the Haute Ubaye valley some 8 km. to the north east at an altitude of some 1900 m. However, the exposure and altitude conditions at St. Paul differ from those on the southern exposed slope of the Barcelonnette basin; in the absence of a comparative study and correlation between the two stations (at present in progress) we chose the climatic conditions prevailing in the region at the beginning of 1982 in preference to the absolute temperature values.

6.2.2. Climatic conditions close by and further away

Annual rainfall : the pluviometric totals and the sliding average over 3 years are given in Figure n° 22. The rainfall in four of the preceding six years exceeded the average (730 mm), in particular for 1976 and 1978. Pluviometry for 1981 was only just above this average. In this period the years 1978 and 1980 were slightly less than average. The sliding averages over

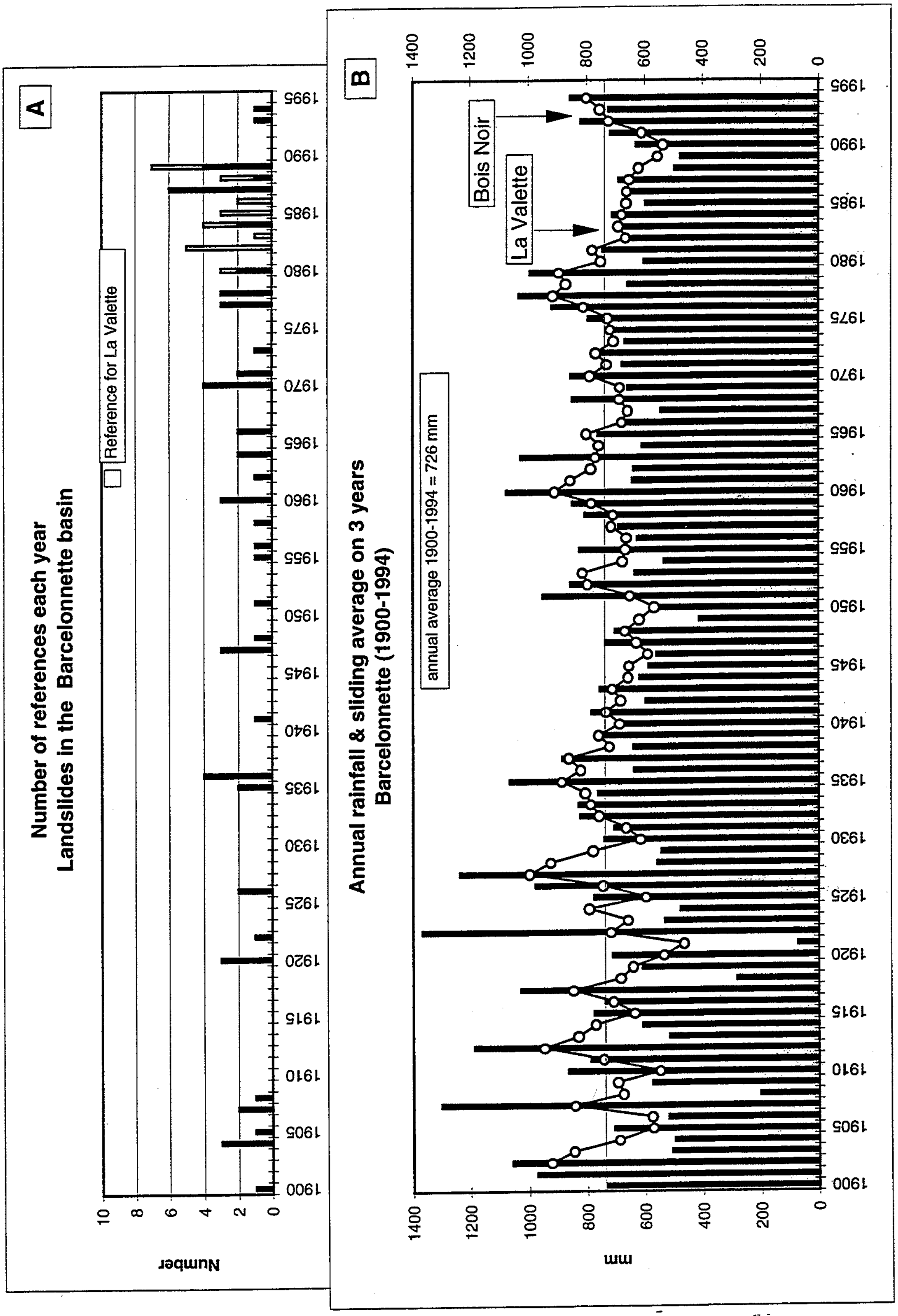

Fig. 22 : Annual rainfall and references in the Barcelonnette Basin

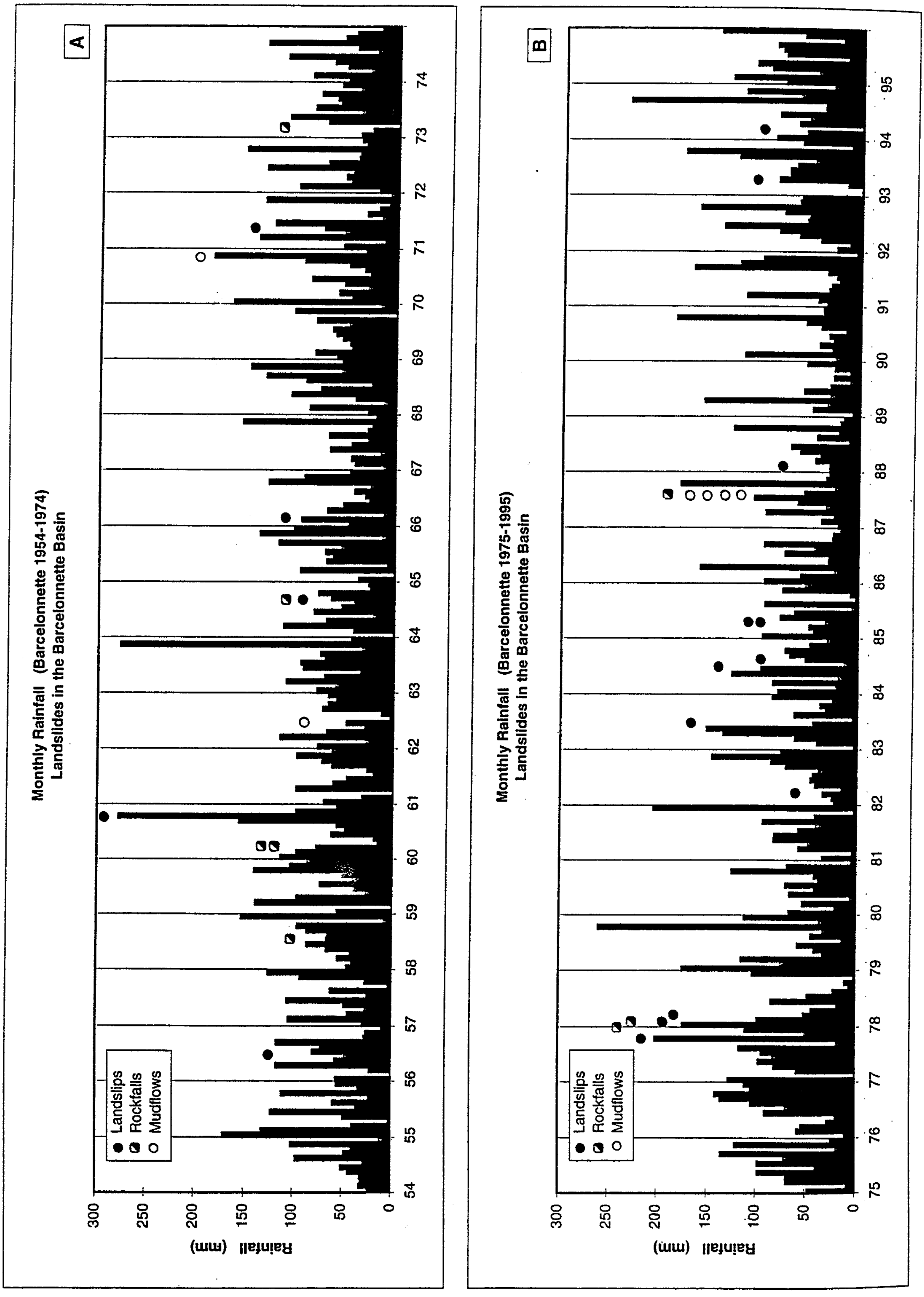

Fig. 23 : Monthly rainfall and landslides in the Barcelonnette Basin

three years give a better idea of the cumulative effect and show that 1982 was preceded by 6 or 7 years of overall excessive rainfall.

Monthly rainfall : Rainfall in the first four months of 1982 was mostly below average, being only 45 % of the total average for these months (Fig. 24a). Rainfall for December 1981 on the contrary, was four times higher than average.

Temperatures : Between December 1981 and March 1982 the average daily temperatures at St. Paul were negative, except for several non-consecutive days during which they were just above zero (Fig. 24b). Maximum temperatures were below 5° and on rare occasions between 5 and 10°. The average decadal temperatures became positive only at the beginning of April (Fig. 24c).

6.2.3. Discussion

- Climatic conditions nearby at the triggering of the landslide are those of several rather cold winter months with relatively low rainfall. They follow a December with very heavy snow showers. The warming, really noticeable at the end of March, marks the real beginning of the snow melt. This water was marginally augmented by several light showers (Fig. 24c).

- Climatic conditions further away are marked by a succession of consecutive years which are either slightly lower, slightly higher or considerably higher than the average. Over forty years of observation there were two periods of 6-7 years (1959-1965 and 1976-1981) in which sliding averages were in excess of normal. The landslide at La Valette commenced after the second.

- The climatic conditions preceding the onset of this landslide are therefore by no means exceptional, either in terms of the rainfall quantities for the preceding months or years, or in terms of March temperatures, which do not indicate a sudden warming which could be responsible for the rapid melting of a very thick layer of snow. These observations, however, should be completed and modified if necessary by data relating to sunshine, the height of the snow and if possible the flow rates measured in the streams nearby.

6.3. Conclusion

- **Triggering :** The relationship between the triggering of earth movements and the climatic parameters are not always obvious. In fact the external conditions (including the covering vegetation) should be taken in conjunction with the internal parameters of the massif : the geometry and the nature of the various layers, the state of the stresses, the development of stresses and also the characteristics of the materials (fatigue, development of cohesion etc.) and the nature of the underground overflows (the existence or non-existence of a free or captive layer). These parameters combine to achieve a balanced state expressed in a safety coefficient (F).

In the case of a slope in a very precarious state of balance (safety coefficient value near to the unit), it only needs a very slight increase in interstitial pressures following light showers, recently infiltrated, to aggravate a critical situation and create instability (F<1). Conversely,

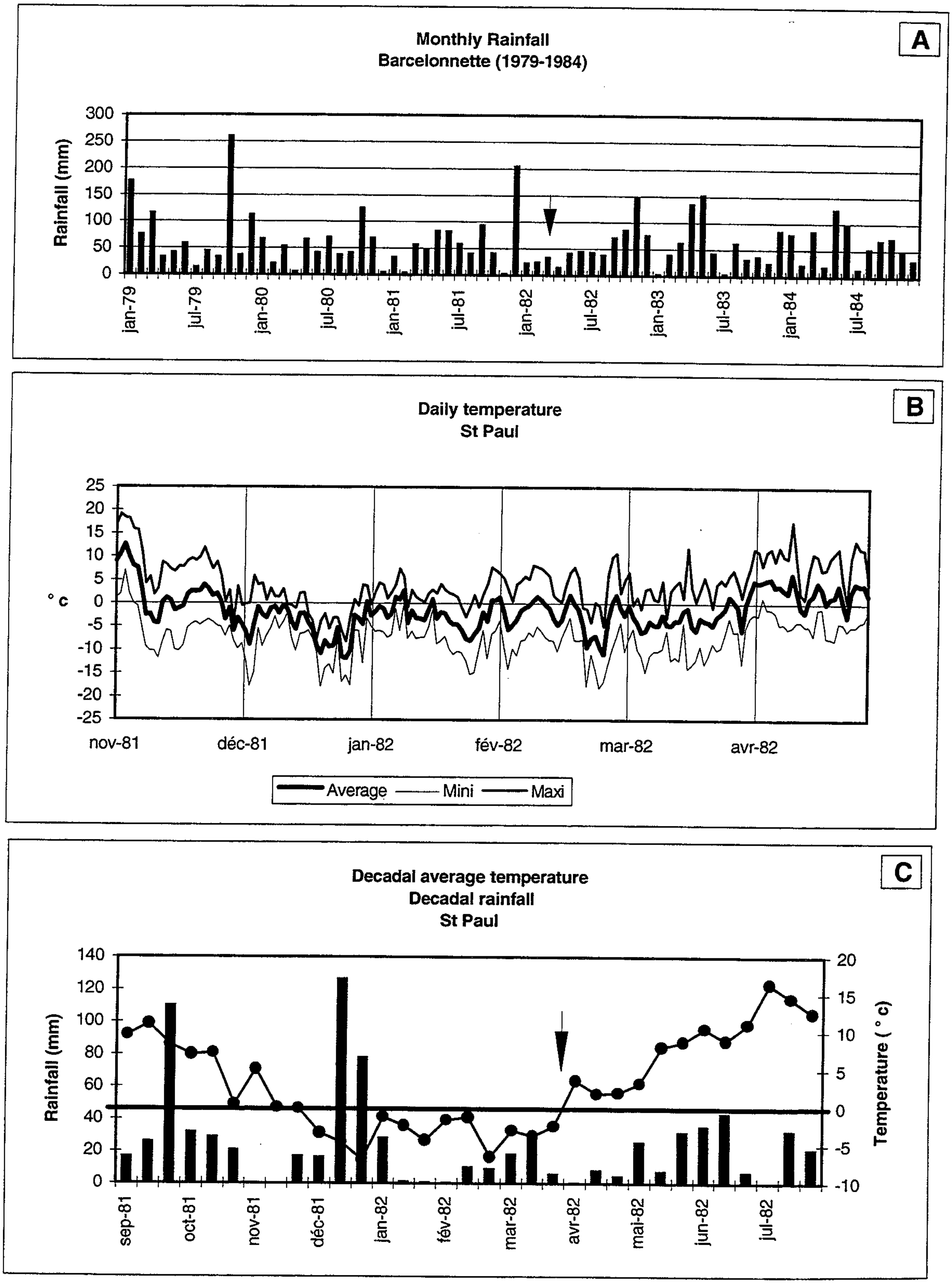

Fig. 24 : Climatic conditions during the triggering of the Valette landslide

for a slope with a higher safety coefficient a sharp drop in the coefficient due to very heavy rainfall leads either to declared instability (an immediate cause and effect relationship) or to a limited balance, in which instability may or may not appear later: the result for a particular climatic incident, close by or at some distance, differs, therefore, according to the initial value of the safety coefficient.

- **Reactivation :** For slopes which have been declared unstable the relationship between the reactivation phases and the climatic conditions (rainfall quantities, temperatures, melts and snow cover) are closer, as for the reactivation of the Valette landslide after the heavy rains of April 1988. This is also the case for slopes in which the seasonal and interannual battement of a shallow phreatic layer is established according to the short response time in relation to the pluviometry.

- **Movement type :** the analysis must also take account of the type of earth movement; the activation conditions for a deep slide and a superficial mudflow are altogether different: in the first our analysis would include rainfall quantities for preceding months for a layer and in the second we would concern ourselves in particular with the rainfall intensity over a short period.

This confirms that the climatic conditions may favour the activation of the instability but they are not sufficient. We should not be tempted, therefore, to establish simple cause and effect relationships too quickly.

Objective N° 3

DEVELOPMENT OF A MODELING FRAMEWORK FOR THE PREDICTION OF LANDSLIDE ACTIVITY WITH RESPECT TO CLIMATE

INTRODUCTION

On the south slope of the Barcelonette basin on the Enchastrayes commune land the Super-Sauze landslide developed over the « Roubines », a 75 hectare stretch of bad-land at the foot of the region's two main summits, the Chapeau de Gendarme (2,685 m) and the Brec Second (2,596 m). The landslide we studied was the subject of detailed geomorphological mapping on a scale of 1: 1000 (Fig. 25), accompanied by a longitudinal profile.

The crown, certainly the most spectacular geomorphological feature in the landscape of this slope stands out between 1970 and 2150 m. high 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. The main escarpment cuts into the moraine coverage (some ten meters thick) and the subjacent "in situ" black marls steep slopes of 100 meters high on average corresponding to declivities of around 60°. Two very visual elements demonstrate this geological discord on the terrain : on the one hand, the light beige colour of the moraine material contrasts with the darkness of the black marls. Secondly, a very marked break in the slope demonstrates the differently-balanced positions of two formations of

SUPER-SAUZE LANDSLIDE

ENCHASTRAYES' COMMUNE (ALPES DE HAUTE-PROVENCE)

Géomorphological map at 1/1000 scale
(Survey of 20th August 1995)

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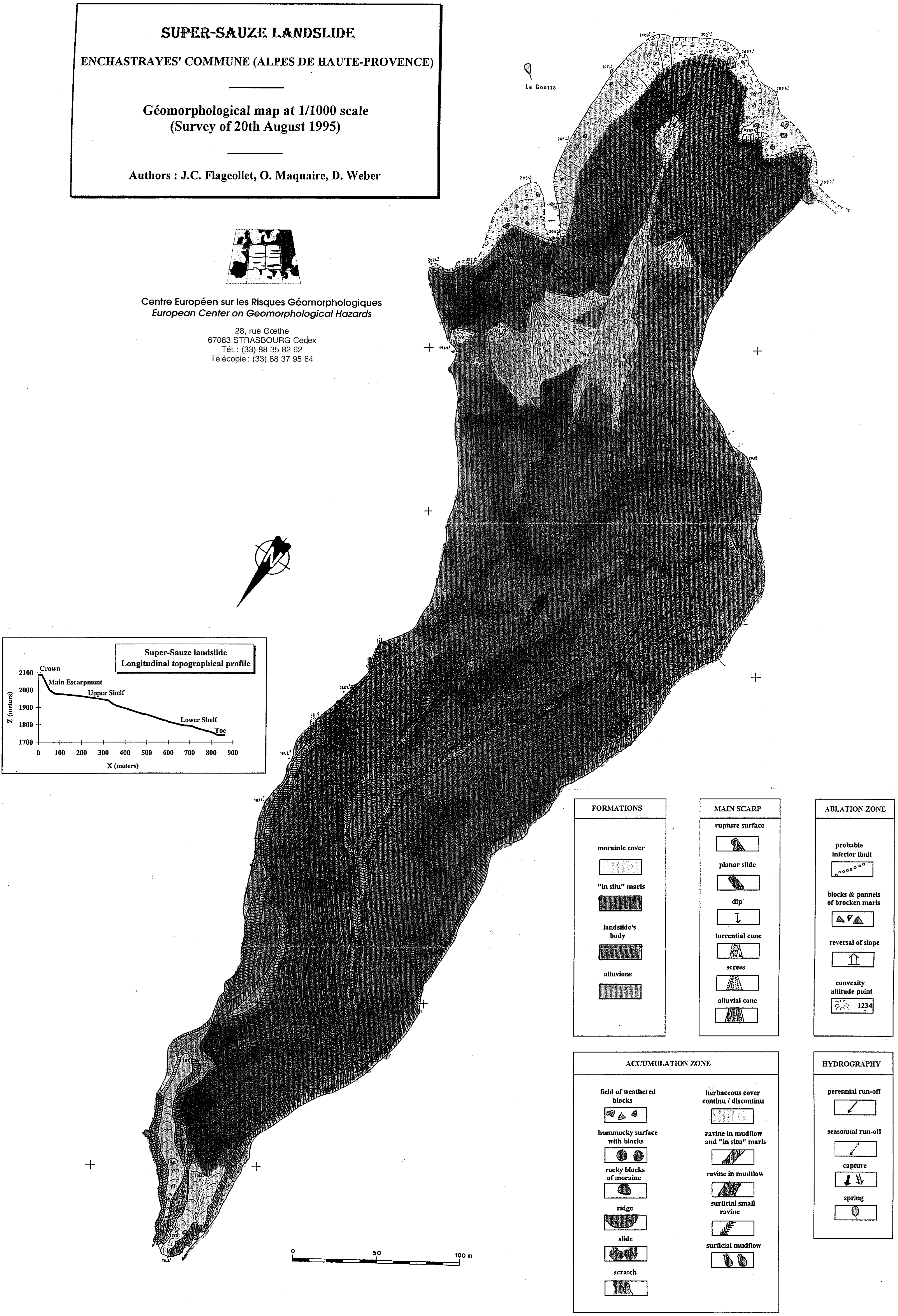

Figure 25

different textures and degrees of granulometry. This superimposition also creates a plane of 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° (see longitudinal profile on the geomorphological map). 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.

Several investigations and field operations have been carried out on this test site with a view to developing a modelling framework to predict the landslide's activity as regards the climate : they include measurements of surface movements since 1991, geophysical reconnaissance by seismic-refraction and electric prospections, continuous rainfall registration close to the landslide at La Rente farm.

Furthermore we are now reconstructing the geomorphological development of this landslide over the last fifty years using photogrammetric processes on various aerial photographs of the site. We have about a dozen pictures taken between 1948 and 1995.

The calculation of several Digital Elevation Models of the sector should provide reliable information on the development of the landslide as a whole and in particular on the retreat of the main crown and the extension of the moving mass, both in surface and in volume. Using the oldest documents, it is possible to reconstruct the initial topographical surface now recovered by the moving mass. In this sense, the aim of these investigations complement the geophysical measurements taken.

I. DÉTERMINATION OF THE SUBSTRUCTURE OF THE POCHE AND SUPER-SAUZE LANDSLIDES BY GEOPHYSICAL METHODS

The object of this study is to determine the substructure of the Poche and Super-Sauze landslides using seismic refraction and electric resistivity. In the first stage (the Poche landslide, 1994 - 1995) we interpreted the results of seismic measurements without computer tools and we used the classic RESIST resistance method to interpret the electrical measurements. In the second stage we propose to improve the seismic interpretation method and to modify the electrical resistivity methods on both the Poche and Super-Sauze landslides. For the latter we will use the « Bayes » statistical method.

1.1. Interpretation methods

1.1.1. Electric sampling

Two interpretation methods are used, the first being the RESIST method (the usual method, designed by Vander Velpen) and the Bayesian method (a new method, devised by J.-J. Schott/EOPG, Strasbourg).

RESIST : For this mathematically-based method a number of layers must be set in advance in accordance with the apparent resistance values observed. They must then be given thickness and resistivity values in the model as a starting point in the model; these will change during the modelling process. The final curve is a function of the values observed and the number of layers fixed.

Bayesian Analysis: This new, statistically-based method enables us to find the most probable resistivity value for each « layer », given that the ground consists of a large number of theoretical layers. These have no physical reality and only serve to subdivide the soil. This theory stems from Bayes theorem for calculating probabilities when full information on a set of events is not available.

Bayes theorem :

$$\mathrm{P(Bj \mid A)} = \frac{P(A / Bj) * P(Bj)}{\sum_{i=1}^{n} P(A / Bi) * P(Bi)}$$

where:	Bj:	the most probable resistivity sought
and/or	A:	the total apparent resistivity measured
	P(Bj):	the à priori probability
	P(A / Bi):	is the law of the often-used Gaussian model

$\sum_{i=1}^{n} P(A / Bi) * P(Bi)$ is the normalisation factor determined using a Markof chain, as it is not possible to explore all the possibilities.

In this way we calculate the probability of a known and observed event as compared with a series of events. It is an inverse probability method.

The Bayesian analysis relates mainly to the study of unprocessed data on apparent resistivity and the distance of current electrodes AB/S.

In order to analyse by the Bayesian method we must know the appropriate smoothing factor which most closely reflects reality. For this purpose we use two statistical criteria - the mean square and the difference between the histograms of a layer for two successive smoothing factors (this factor minimizes the difference of integrals for two consecutive smoothing factors and for the same layer.

Once the best smoothing factor is determined the analysis proceeds in several stages.

- **Transformation of files** into an appropriate format for Bayesian analysis. These files mainly contain the apparent resistivity values, the distances between current electrodes, a smoothing factor for the curve, the interval at which resistivity is explored, the number of iterations required, the number of very wide curves taken and a sufficiently large depth for the given substratum.

- **Analysis .** This is a two stages process :

* Calculation of the curve and extraction of the characteristics of each « layer » of the curve, such as the most probable resistivity and the thickness of each layer.

* Analysis by the Bayesian method and visulalisation of the soil resistivity profile with the depth in abscissa and the average and most probable resistivity values as ordinate. This analysis also allows us to see the histogram of resistivity frequencies for each layer and to know whether the most frequent value is respresentative for a Gaussian distribution or if it is not representative for a bimodal distribution.

1.1.2. Seismic

The shots in the centre are necessary in order to define the speed of the first milieu. In fact the direct wave signal occurs more over outline than over shots at the end. However, these shots are not sufficient to reach great depths. The speed of the milieu given by the first refracted wave is not contained and the speed of the second is often absent.

These shots serve definitively to compare the speeds of the first milieux by the manual and automatic methods, knowing that the latter is accurate.

Interprétation by Geophil 2D : This programme enables us to determine the hodochrons and the inverse of their slopes (or ground propagation speeds) from a computer pointage. The results can be used in the status if the quality of the signal is good, if static corrections are not necessary and if the reflectors are regular. However, filtering is recommended if the noise signal is weak. Their limits are chosen by means of a spectral analysis of the pure signal and another of the pure sound. In the same way, statistical corrections must be made when the relief is irregular. These are placed on the original hodochrons. New droits are thus calculated, and hence also new speeds and thicknesses. If the shape of the reflectors is also irregular it is advisable to use an additional software called THORN.

1.2. Main results obtained for the Poche landslide

1.2.1. 'Seismic' results

Layer no. 1, an upper layer of reworked and deteriorated material is less than 4 metres thick at the foot of the landslide in profiles L1 and L2 and it thickens progressively to a maximum (of the order of 8 to 10 metres) in L7 and L8. At the top of the landslide it thins out again.

The ratio between the speed of the two layers is in the region of 2. The lower layer of the unstable mass (layer no. 2) showing higher wave velocities is not so well circumscribed; only 9 limits give us an indication of its thickness. This second layer is not present over the whole of the landslide as it can no longer be detected upstream of the L7 profile.

The third layer constitutes the rocky substratum in place, according to the speeds obtained (between 2000 and 4000 metres per second). These include a higher uncertainty than the preceding speeds because of the late arrival of signals which prevents a sufficiently clear distinction between the signal and the noise. Nevertheless the results are still coherent; in fact, the marls have theoretical speeds of between 2000 and 3000 metres per second. Waves with speeds of more than 3000 metres per second are very probably those refracted on the discontinuous limestone banks which characterise this geological formation.

1.2.2. 'Electric' results

Because of the low depth of investigation of this prospection method, it is only possible to see the base of the first layer. However, it does enable the definition of several other layers which do not show seismic refraction. The results obtained by the two methods for the same measurement bornes are identical for the thicknesses determined, which demonstrates their validity and complementarity (though in electric sounding the figures obtained are averages by profile).

In order to check if we are observing the same strata from one electric sounding to another, we are obliged to make use of characteristics relating to the resistant layers (thickness × resistivity = constant) and conductors (thickness / resistivity = constant). Four layers can be detected in the lower part of the landslide. This increases to five in the centre, the additional layer being on the surface, a fine dessicated crust with a very high resistivity. It will be noted that soundings S7 and S10 show four layers in the same central sector; they are situated in a humid depression zone, which explains the absence of the crust. In the high part of the landslide we can also measure five layers; nevertheless, the first is more humid and has a higher conductivity than that detected in the central part of the landslide.

The homogeniety of the terrain is verified by two asymetrical profiles of the surface type which allows us to compare resistivities first at one and then at two metres from the ground. Against all expectations we observe that at two metres the land is very homogenous with regard to the use of the electrical resistivity prospection technique.

1.2.3. Analysis

Interpretation of the results of geophysical prospections on the Poche landslide leads to the determination of three distinct layers (Fig. 26) by the seismic refraction technique, while only one can be detected by electric soundings. On the surface, layer no. 1 comprises degraded material reworked by earth movements. Beneath it the second layer, also of displaced material, is more compact and closer to the original. The third is the rocky substratum in place under the surface of the landslide. These three layers are composed of material from same geological formation, in this instance black marls, the differences in depth residing solely in their degree of compaction and degradation.

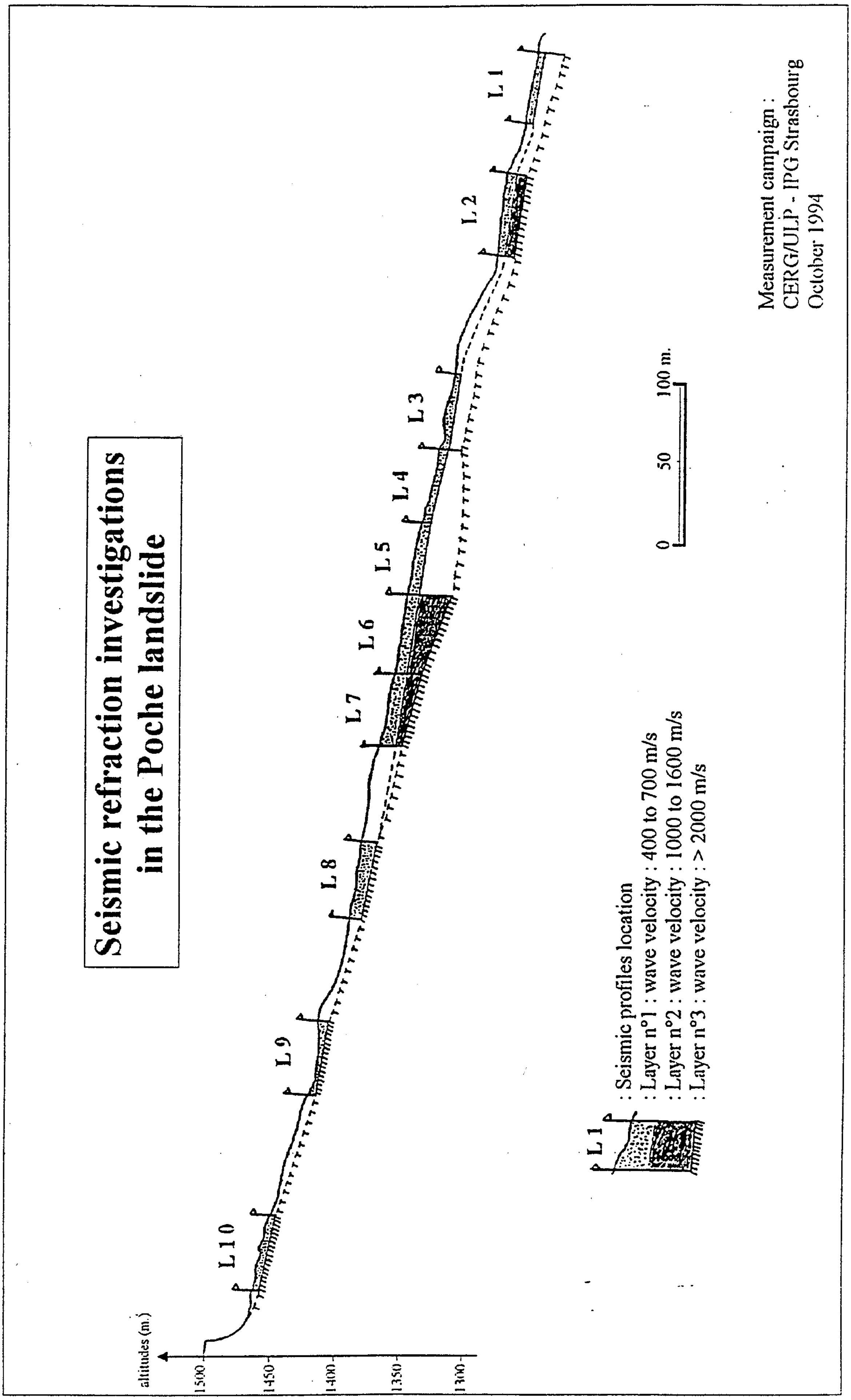

Fig. 26 : Seismic refraction investigations in the Poche landslide.

1.3. Main results obtained on the Super Sauze landslide

1.3.1. 'Electric' results

- by the RESIST method

For the 15 soundings carried out, five of which were croisés, we observed that the same uncertainty values could be obtained by several different models. Generally speaking models comprised 4 « layers », with the exception of soundings E3 and E8, which contained 5 and 3 layers respectively.

We carried out croisés profiles for soundings E1, E2, E3, E4 et E6. The two lines AB and CD of soundings E1, E2 and E4 are very comparable both in the speed and thickness of the model. However, the lines AB and CD of profiles E3 and E6 differ, dobtless because of their orientation and because a tabular surface was hypothesized. In fact in both cases the AB lines are oriented in the direction of the landslide while the CD lines are oriented perpendicularly, crossing several ravines and butting against the flanks of the landslide. The crossing of the ravines gives rise to lateral heterogenieties and thus to jumps in resistivity when the MN electrodes separate. Reaching the flanks of the landslide provokes a rise in restivities which is not visible on the AB line. This rise is due to the error arising from the hypothesis of a tabular surface.

- by the BAYES method

A statistical test on the smoothing factors proved that the best was equal to 2. On the other hand, 200 iterations gave a result which was better than 100. The following parameter is the interval of resisticity explorations which were agreed as being between 1 and 1000 ohm/m., as it was evident that exploration between 5 and 500 ohm/m was insufficient. The fourth parameter is the « a priori » depth of the substratum, which we set at 20 in view of the seismic results. To a lesser extent the thickness of 0.5 metres set for the first layer influenThese the final speed of the resistivity profiles of the soundings.

The main result of the Bayesian analysis is given in the form of a graph showing the resistivity profile of a layer, with the AB/2 distances as abscissa and the resistivities as ordinate (Fig. 27). Two restivity values are given: the modal value, which is the most probable value (or geometric average) and the average.

This graph is associated with a file of data in figures giving the average resistivity, the modal resistivity, the thickness and the depth for each layer of each sounding.

Bayesian analysis also allowes us to visualize histograms of resistivity frequency for each layer. Generally speaking, if the parameters are well chosen the histograms are presented in the form of a very narrow Gaussian curve, which means that the restivities are well contained. if the parameters are well chosen (Fig. 28).

The general speed of the resistivity profiles of the soundings presents two leading troughs (layers). Generally the first has ha higher resistivity than the second. Once the leading layers are localised the limit of the substratum lies between the last leading layer and the substratum.

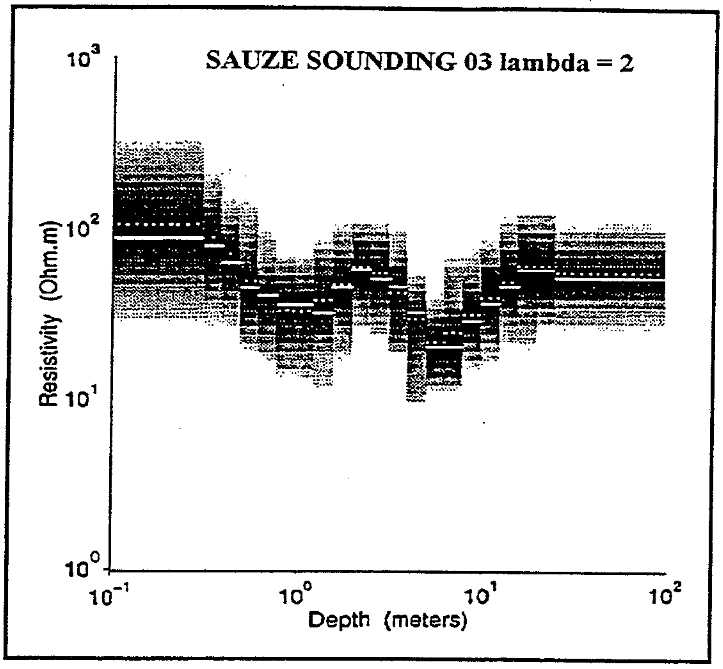

Fig. 27 : Resistivity profile of electrical sounding n° 3.

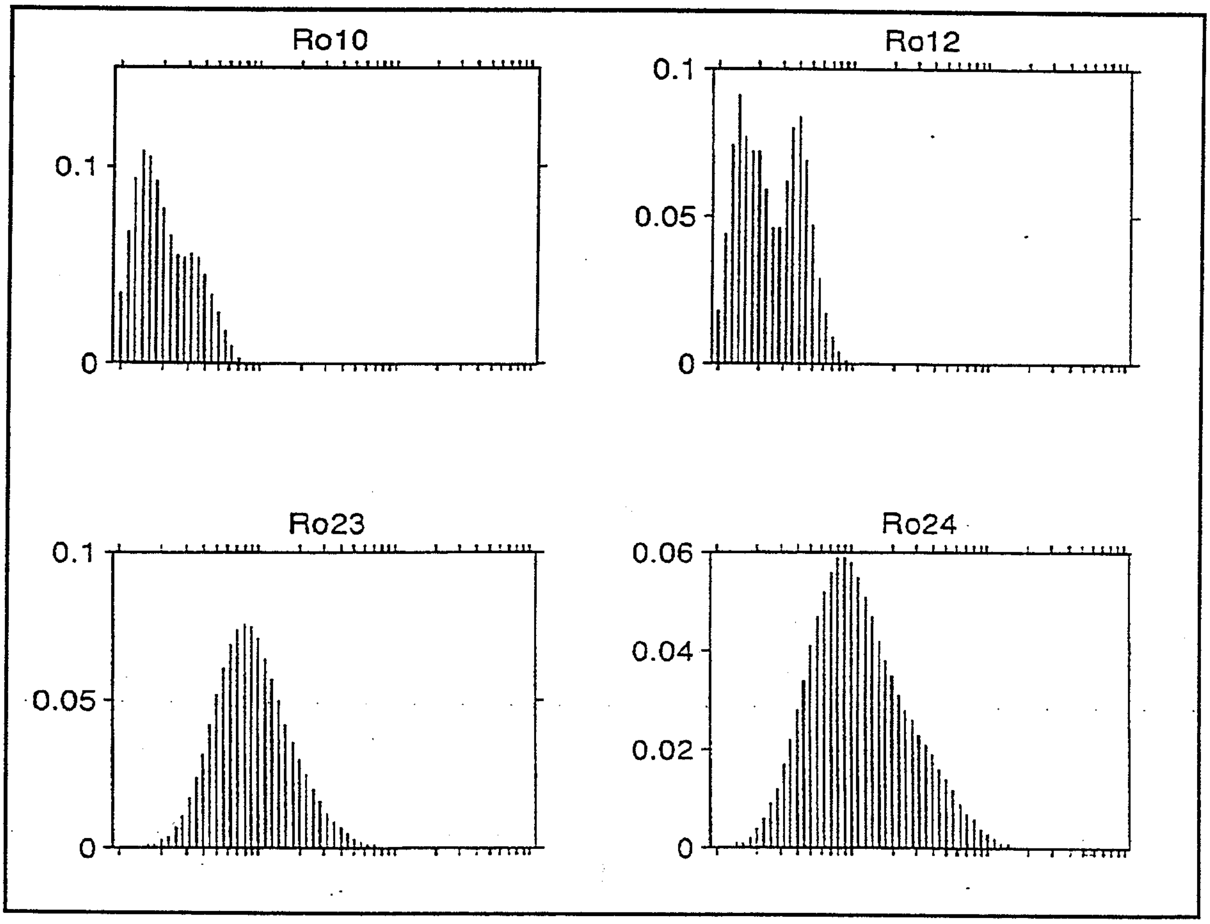

Fig. 28 : Resistivities distribution of different electrical soundings in Super-Sauze landslide.

There is an uncertainty, therefore, between the depth of the leading layer and the substratum, which can be ascertained by the seismic method or if necessary by other methods such as the geotechnic.

- Comparison of RESIST and BAYES

It seems obvious that RESIST interpretations (alone or combined with Bayes) are much less detailed than BAYES interpretations. It seems that the last leading layer detected with Bayes and the substratum are changed into a single intermediate layer with RESIST. Furthermore, with regard to depth, if we multiply the comparative elements of thickness over resistivity by 2 we reach the same result as by Bayesian analysis. This is altogether plausible, given the uncertainty of the RESIST models. RESIST and Bayes can therefore be rendered compatible.

1.3.2. 'Seismic' results

Sixteen profiles were carried out (Fig. 29). It would not have been possible to interpret the shots from unprocessed data this year because of the poor quality of the signal. In fact the seismic signals were much harder to detect because the terrain and the meteorology were both unfavourable. It was necessary, therefore to filter systematically after spectral analysis of the pure signal and the pure noise.

Signal frequencies proved to be between 25 and 120 Hz. We therefore used a passband frequency filter (25 Hz lower frequency and 120 Hz higher frequency). However two seismic profiles L4 and L11 remain uninterpretable, as the signal and the noise frequencies cover each other and they cannot be distinguished.

For the Poche landslide we are observing 3 milieux : a very degraded milieu with a slow speed (between 400 and 700 m/s) which is to be found over the whole of the landslide, an intermediate layer which is only present in places where the speed is a little higher (between 1000 and 1600 m/s), and finally a marl substratum in which the speed exceeds 2000 m/s. However, for the L1 and T3 profiles the difference in speeds between the first and second milieux is not significant. We can offer several hypotheses; the first is that the 900 m/s of T3 corresponds to the second milieu and that the first does not exist; the second is that this speed corresponds to an average of the speeds of the first and second milieux. In fact it is possible that the milieu is so small that it is undetectable in seismic profiles.

Aside from this, the major problems facing us were advances or delays in some signals on several geophones.

If these irregularities were on direct and inverse shots we could have said that the refractor was not level and we could have determined the shape of the refractor using THORN software. However, these irregularities only occurred on one or two shots. The problem was doubtless due to a lateral energy loss which was not visible in a two-dimensional interpretation. It would be useful to interpret in three dimensions to overcome the problem.

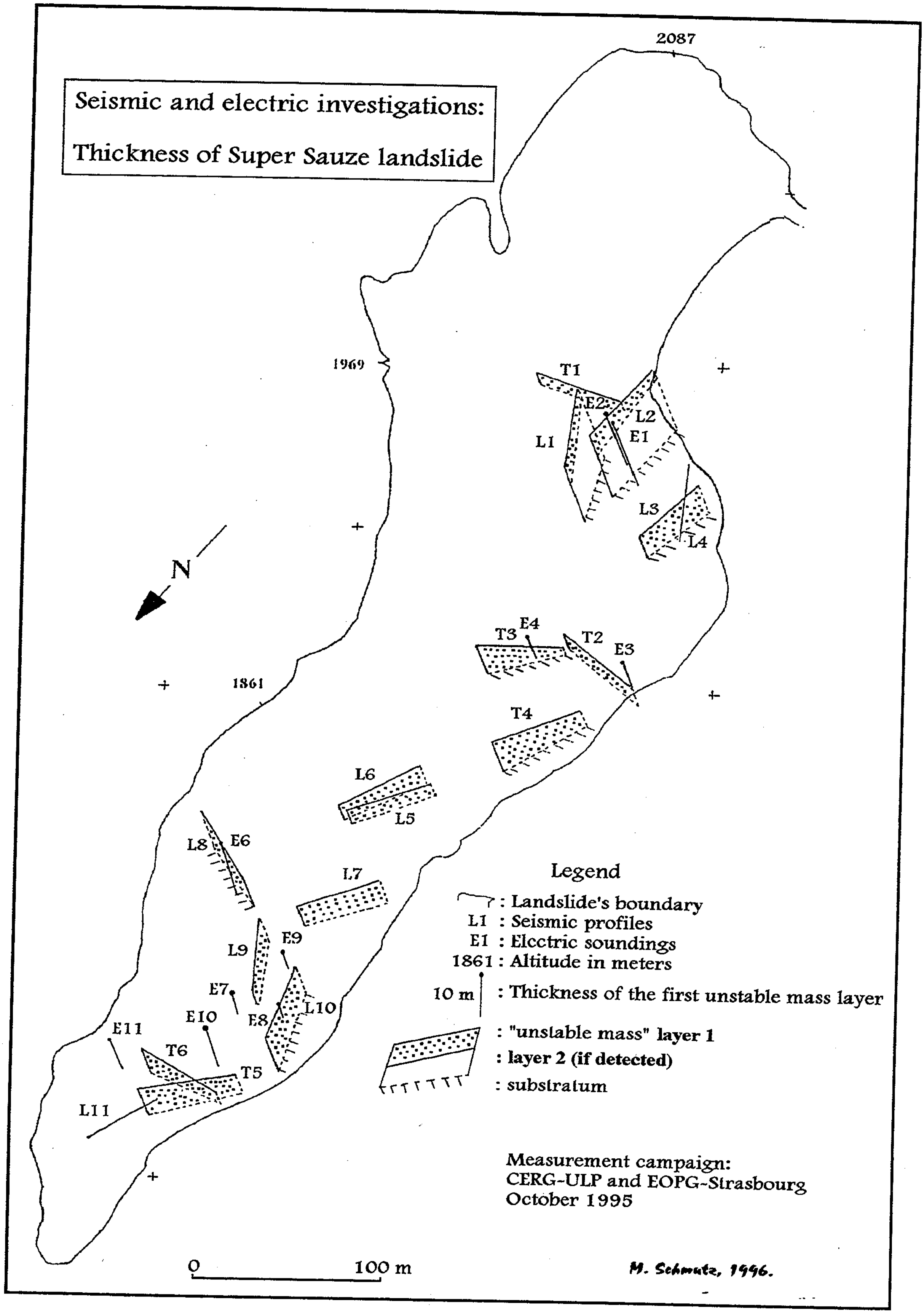

Fig. 29 : Seismic-refraction and electrical soundings results in the Super-Sauze landslide.

1.4. Conclusion

Considerable progress has been made on methods of interpretation. In fact we have automated a seismic method and we have considerably increased the possibilities of electric interpretation. However, several problems must still be resolved. In seismic interpretation it would be better to use a three-dimensional method which would allow for lateral energy losses which cause delays (or advances) in the arrival of waves.

In electric interpretation we can now give a real uncertainty value for the depth of the base of the substratum. Seismic or geotechnic methods can be used to ascertain this uncertainty value.

With regard to acquisition methods it would be interesting to carry out further « seismic refraction » profiles and to carry out « seismic reflection » as a multiple cover in order to obtain a maximum of data on the terrain. for electric interpretation, on the other hand,Wenner's technique seems to be indicated, in order to avoid jumps due to the displacement of the potential electrodes (MN). However, the depth of the investigation would be lessened.

As our data on both landslides is limited their substructures were only known at a few points. It is therefore impossible to extrapolate them precisely in three dimensions at present.

II. MEASUREMENTS OF SURFACE MOVEMENTS

2.1. The surveillance network

In August 1991 the surveillance network for surface movements initially comprised some 40 points taken from two stations : 15 points were placed on the body of the landslide, with 14 more along the crown, 4 on a small unstable zone at some distance from the main movement and the last 7 in various neighbouring sectors, some of which could serve as stable reference points. Fourteen measurement campaigns were carried out between 14th August 1991 and 24th May 1996. For various reasons connected with work on the land, these campaigns did not provide information on all points every time. Ten of the 15 markers initially placed on the most active sector have disappeared during these four years. Most have been replaced by new markers installed nearby.

In June 1996 this surveillance network will be entirely reorganised. There will be two measurement stations in the form of concrete ausculation pillars with a drilled plate which centers automatically the theodolite; this will not only improve the quality of readings but will also reduce the length of measurement campaigns.

The site of the Super-Sauze landslide is at a relatively high altitude and therefore snowbound for a long time, so campaigns to measure displacements are usually possible only between May and November. Because of this the periodicity of topometric readings it is not always obvious to show an exact correspondence between earth movements and rainfall.

2.2. The main results

Movements are analysed spatially and temporally using graphics showing cumulative horizontal movements in terms of time, or by average speeds calculated according to the time elapsed between two successive topometric readings. Such curves have been established for the mobile reference points which are the most characteristic of the landslide.

Figure n° 30 shows on a simplified geomorphological map of Super-Sauze landslide the vectors linking for the most mobile reference points their original positions of August 1991 with the present positions. The accompanying graphs are a more accurate indication of the positions noted during successive measurement campaigns. These vectors show the main direction of the movements in the body of the unstable mass, but without regard to the time factor. The average speed value noted on the graphs are only given as an indication of the spatial distribution of the movements over the whole moving mass (the periods considered for the calculation of these values are not all the same).

The three first generation points on the upper shelf are no longer in use; during their follow-up periods they showed annual speeds of between 3,9 and 7,6 meter/year. The zone recording the most significant movements is immediately below the upper shelf (points 16 to 20); movements recorded here are of the order of 10 m/year. This is the sector where the slopes are steepest. The vectors for points 10 to 15, placed on a transverse profile, offer a perfect demonstration of the lateral decrease in movements from the centre of the unstable mass towards its edges. Reference points 8 and 9 bear witness to the activity in the lower part of the flow, which is advancing by 1 or 2 m/year.

The altitude of reference point no. 8 increased with time, unlike the other points monitored. This indicates a swelling of the lower shelf due to accumulation of displaced material. The speed of the Sauze landslide was therefore reduced by the earlier topography in the lower part of the talweg in which it developed initially.

III. CORRELATION BETWEEN MOVEMENTS AND RAINFALL

The rainfall measurements used at present in these analyses are taken from the Barcelonnette station, as pluviograph readings have only been available from la Rente since 1994. The rainfall quantities are lower at Barcelonnette but the variations between the two stations are concomitant.

The movements collected from six points which are typical of the whole of the Super-Sauze are given in figure 31. Points n° 8 and 9 are situated in the lower part of the landslide (lower shelf and toe), 13 and 14 midway and 16 and 17 upstream, just under the upper shelf. The development of the whole is the same for these six points, with an appreciable decrease in movements from upstream to downstream.

Variations in average speeds between different measurement campaigns are given in figure 32, which also shows the number of days and the quantity of rainfall recorded at the Barcelonnette station for each period.

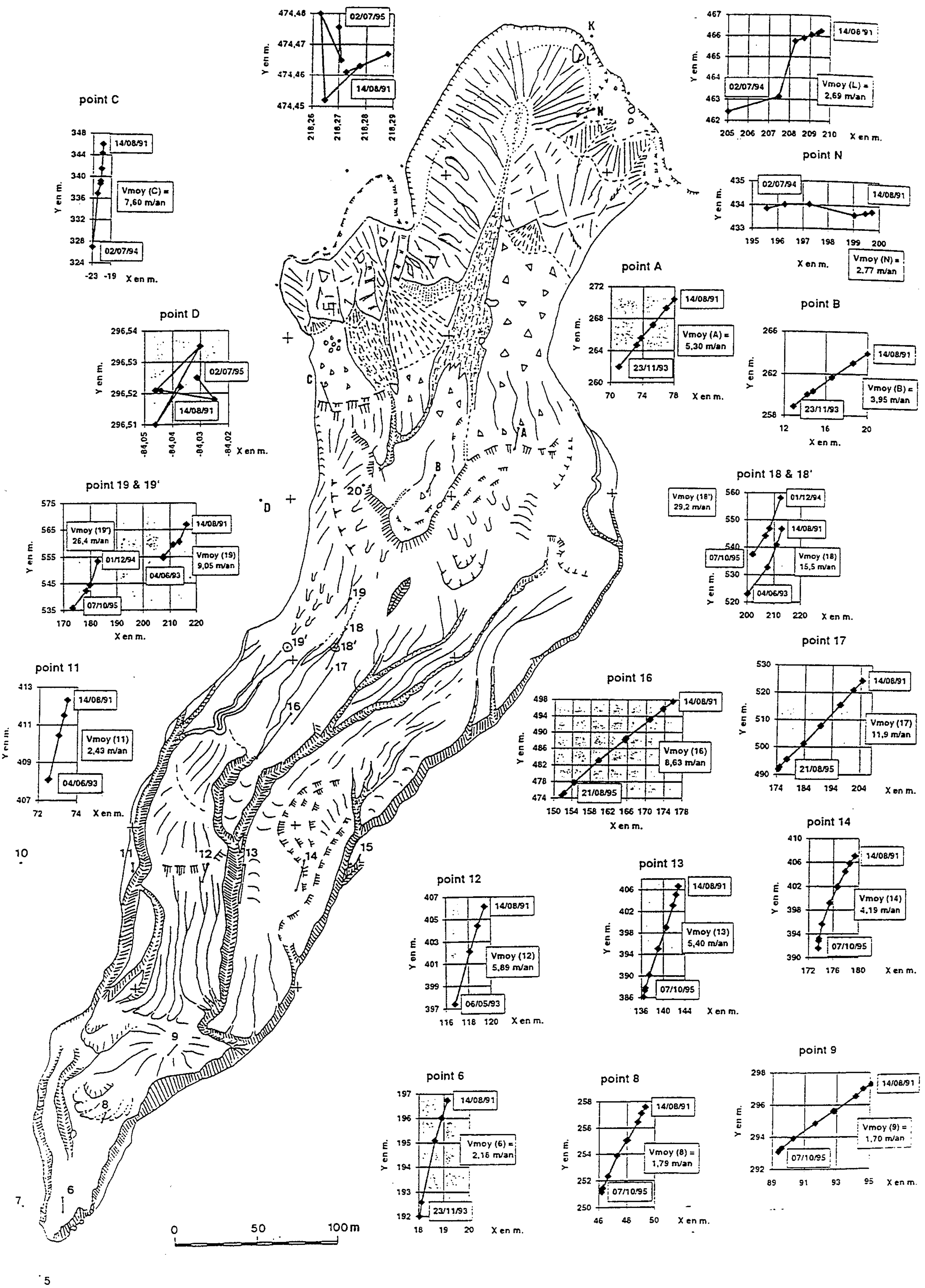

Fig. 30 : Surface displacements on the Super-Sauze landslide.

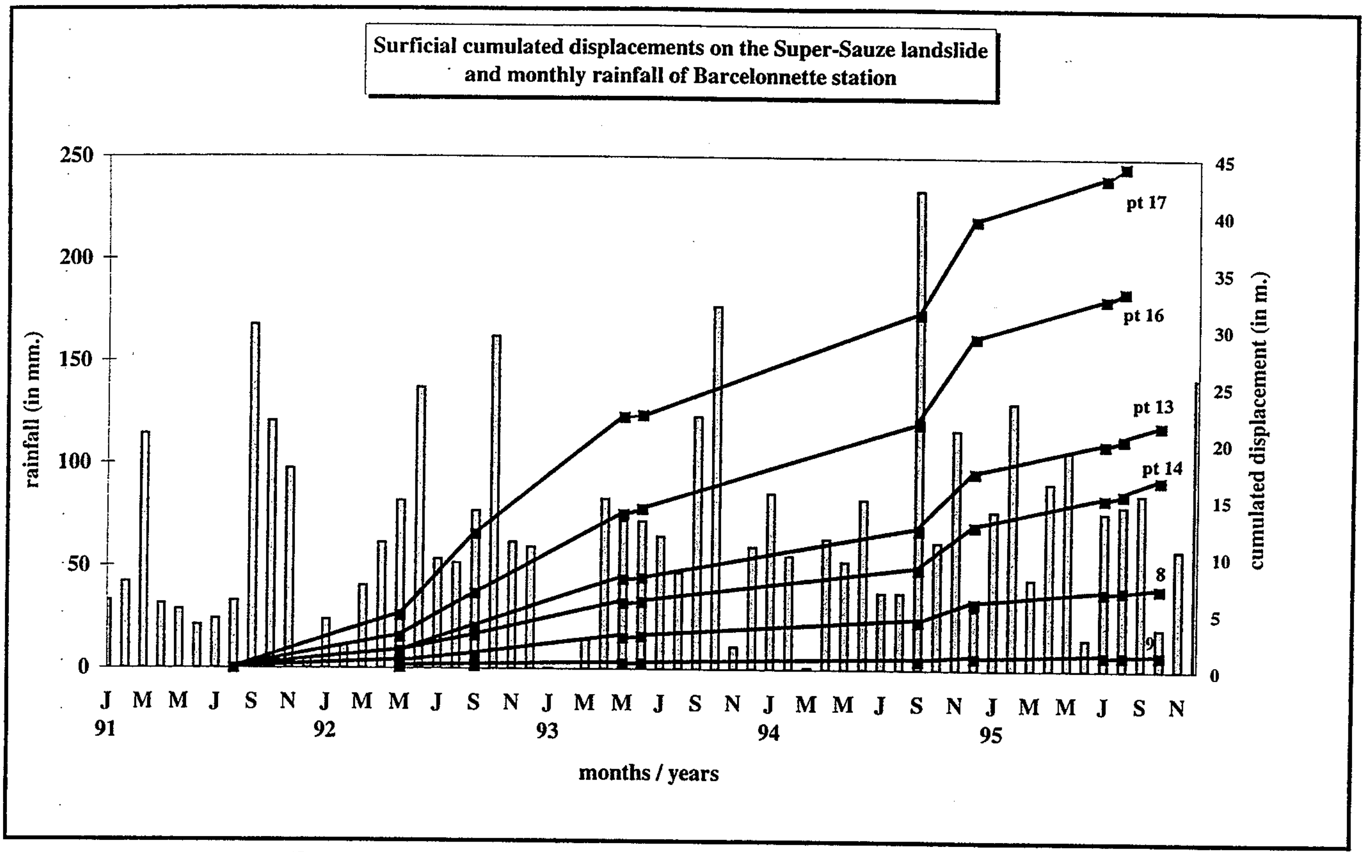

Figure 31 : Surficial cumulated displacements on the Super-Sauze landslide and monthly rainfall of Barcelonnette station.

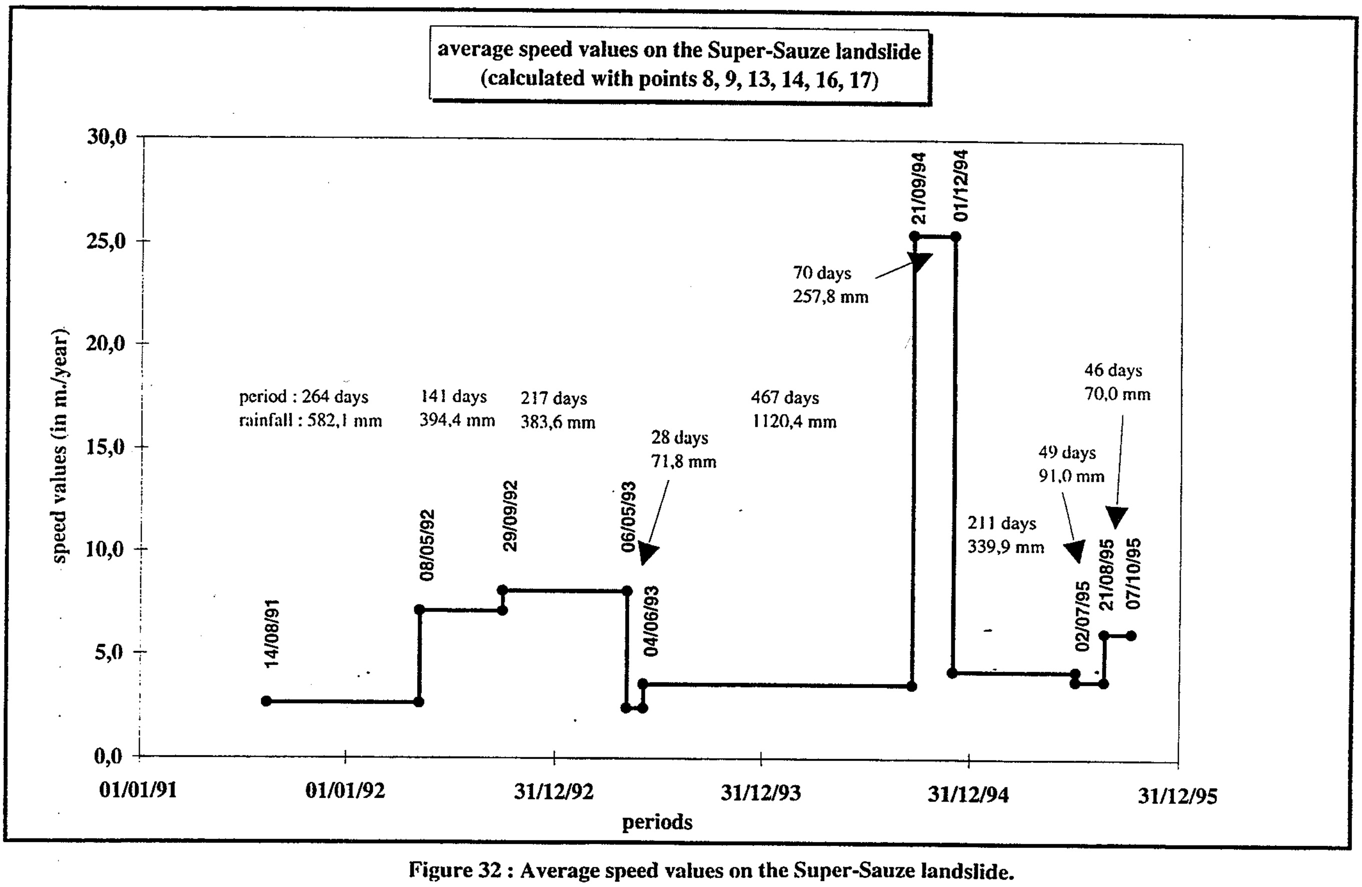

Figure 32 : Average speed values on the Super-Sauze landslide.

The main objective is to obtain rainfall measurements at an altitude close to that of the Super-Sauze landslide. We also compare the rainfall recorded at La Rente with that recorded at Barcelonnette (available since 1928) and Jausiers (available since 1961), which are located at the bottom of the Barcelonnette basin.

4.2. Current results

These results relate to the last four months of 1994 and the whole of 1995, i.e. a series of 16 months. Daily and monthly readings have been compared with those of the Barcelonnette and Jausiers stations. The following points emerge from this comparison, illustrated by figure 33:

- For the whole of the period under consideration the monthly precipitations recorded at La Rente were higher than those at the other two stations (around 18 % higher than those at Barcelonnette and 32 % higher than those at Jausiers). This illustrates the altitudinal pluviometric gradient, a normal and recognised phenomenon. Nevertheless showers are sometimes heavier or equal at Barcelonnette for the winter months of December 1994 and in February, March and December 1995. This observation may be explained by the technical hypothesis that the quantity of snow recorded at La Rente, which is higher than at Barcelonnette, may be underestimated because of bad interception by the pluviograph funnel.

- The Barcelonnette and Jausiers stations are located at altitudes of 1,140 and 1,510 metres respectively; paradoxically, the Barcelonnette station is the wettest. This can be explained above all by the particular orientation of the Barcelonnette basin, open to flows from the west (the most frequent), from which the Jausiers-Lans station is relatively sheltered. Climatic situations developing from the north and east flows are rarer.

- During the last four months of 1994 two humid months, September and November, alternated with the two very dry months of October and December. The month of October was particularly surprising as it is traditionally the wettest month in this region, according to statistics over the last 40 years. The heavy rains of November were concentrated in the first ten days, and were followed by an exceptionally long dry period (28 days) until the 9th December. There were only three wet days throughout the whole of December. This initial information provided by the Rente pluviograph and confirmed by those at Barcelonnette and Jausiers enables us, therefore, to observe the absence of snow at the end of 1994 and in particular at the beginning of the winter of 1994/1995.

- The months of January and February 1995 will have been more favourable from this standpoint. However, we note that the month of March was particularly dry, and was followed by two very wet months. Finally, in spite of a very dry early winter in 1994 the winter-spring period 1994/1995 can be regarded as wet on the whole. For the second consecutive year October was exceptionally dry. Heavy snowfalls in November and particularly in December are also relatively unusual for the last decade. Definitively 1995 was a showery year and even ranks as the seventh wettest of the last 68 years.

- On this station as in the two others located in the basin, the years 1994 and 1995 confirm the tendency to a rise in rainfall which began in the 1990s. This evolution has to be

We observe high movement speed taken in two separate occasions :

- from spring 1992 to spring 1993, in relation to the heavy rainfall recorded throughout the whole of 1992, which was the wettest since 1979 : the high speeds from May to September correspond to heavy rainfall in May and more particuarly in June ; the even higher speeds between September 1992 and May 1993 correspond essentially to heavy autumn rainfall,

- in autumn 1994, following an exceptionally showery September.

A very good correlation is evident between the heavy rains of September 1994 (234.1 mm) and the significant movements recorded for all the points between the 21st September and the 1st December. The very high speeds (some 5 times higher than the averages calculated over the whole of the four years' monitoring) recorded during this short 70-day period confirm the significant role of rainfall in some autumns. The apparent response time is around one month (high speeds in October-November after the rains of September), but it may prove to be shorter if movements accelerated at the beginning of the period from the 21st Setpember to the 1st December.

Between the two particularly wet years of 1992 and 1994, 1993 was again under the average of 730 mm established for the period from 1954 to 1994. It marks a break in the constant rise in rainfall observed since the beginning of the 1990s. The winter of 1992/1993 and more especially the first three months of 1993 were particularly dry, and there was no snow. Although a subsequent technical problem deprived us of data taken in November 1993, we note that the landslide does not seem to have moved significantly in the period from June 1993 to September 1994.

We have readings for immediate rainfall at la Rente, not far from Super-Sauze, at an altitude similar to that at the foot of the landslide. We will also have effective rainfall figures when the climatic station is installed (June 1996). We intend to take daily movement measurements during several campaigns of one or two weeks.

Generally, with regard to climatic conditions, we should mention here that topometric monitoring of the Super-Sauze landslide began in 1991 and coincided with the commencement in the same year of a rise in rainfall which seems to be continuing to the present date (see obj.2 chapter V.5.3.2). Analysis of the development of a landslide as large as the one studied here should be carried out over several decades as well as annually or pluriannually if it is to take account of all the superimposed cyclic climatic fluctuations.

IV. RAINFALL MEASUREMENT AT LA RENTE SINCE 1994

4.1. Reminders

The pluviograph at La Rente was installed in the Barcelonnette basin in August 1994. It is located at an altitude of 1678 metres close to the Super-Sauze landslide (Enchastrayes commune). Rainfall has been recorded there continuously since 1st September 1994.

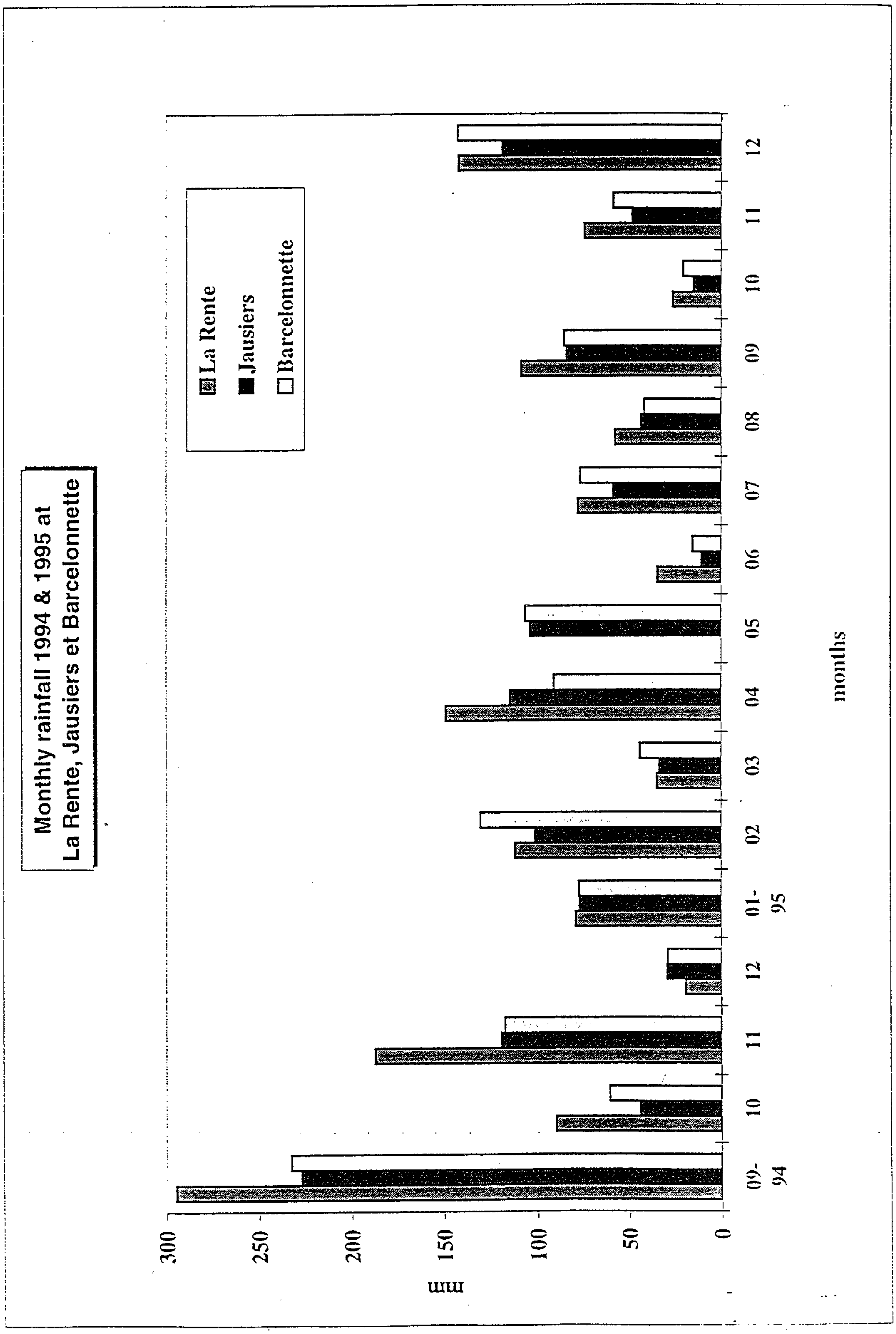

Fig. 33 : Monthly rainfall 1994 and 1995 at La Rente, Barcelonnette and Jausiers

considered in the "cyclic" development observed for the Barcelonnette station over the whole century.

CONCLUSION

The Barcelonnette basin has proved to be exceptionally rich in gulleying and landslips. These have long been a problem to a rural population which was quite large until the 19th century and to people living in the valley since communications and tourist facilities were installed. For this reason efforts to control the torrents were among the most assiduous and the most spectacular in the French Southern Alps from the end of the 19th century up to the first world war. The devastating torrential flooding has almost ceased but sliding still occurs and new landslides appear periodically. This scientific programme completes all the other research projects which have been undertaken over several decades because of the magnitude of the risk.

The first important result, indispensible to any consideration of the development of these phenomena with regard to future climatic changes, is a full register of earth movements in this basin, both in space and in time. Old and new landslides have now been located on various scales; this will be useful to developers and it authorises us to draw several scientific conclusions.

There has been quite extensive sliding at sites which farmers have subsequently stabilised and cultivated, but none has been on the scale of the four large landslides studied here. Three developed naturally without human intervention and the largest (Poche), triggered seventy years ago, is still spreading, in spite of reforestation and the growth of forest trees. The increase in the number of small landslips is due to the fact that unprotected banks are destabilised by torrential erosion and some of them are beginning to take on sizeable dimensions because of progressive deterioration. New landslides have also appeared recently at Bois Noir, due to the break-up of the black marl embankments of rural and forest roads which have been widened to take modern machinery.

The historical inventory confirms the importance of landslips, which represent over 60 % of the landslides in the basin for 150 years, in spite of reforestation and the correction of torrents; it could even indicate a rise in their number over the last twelve years, though in reality this is confined to the Valette landslip, the accelerations of which are frequently mentioned in archives and in the press. Landslides occur at very different times of the year but predominantly in spring and it is tempting to see a connection with late melting snows.

We were only able to trace rainfall development since the beginning of the century by extrapolation; this could affect the facts to some extent, but it does not distort them. One of the most notable general results is precisely the absence of a significant development towards an increase or decrease in rainfall, along with the consistency of the interannual variability. The annual average maxima and minima recur every 35 - 40 years, separated by differences of 300 to 350 mm. Intermediate « cycles » with lesser amplitudes recur every 15 - 20 years. We are nearing the maximum of a « rising » period in annual rainfall. The detailed examination of this development on various timescales (multiannual, annual, seasonal and daily) leads us to conclude that the cause and effect relationship between rainfall and the triggering of landslides is far from being the only one, nor is it even evident. On the other hand, this relationship is much closer with regard to reactivation. The detailed study of triggering and reactivation conditions on the large landslide at La Valette confirms these conclusions.

This being so, we believe it would be risky to try to model the occurrence of new landslides from possible forecasts of future climatic developments in the basin; furthermore such a forecast must include other climatic parameters, such as temperature and effective rainfall calculations.

However, we could model the activity of existing landslides, provided the activity measurements and the climatic data were complete. This has been commenced and will continue at Super-Sauze, one of the large landslides in the sector. Over the last two years we have been able to obtain some of the information needed, in the first place about the structure and geomorphology of the landslide and the climatic indications which can be drawn from them. The geophysical auscultation was difficult because the surface was irregular and access was difficult; We tried several methods; Bayesian analysis of electrical resistivity produced promising results. The land surface displacement speeds were significant, being several metres a year in some places, and in particular they show a close correlation with heavy rainfall, both annual and monthly. The land may even react very rapidly to rain, but this remains to be verified and measured; this will be possible as soon as we can undertake movement measurement campaigns continually, at least during certain periods of the year, and make a closer estimate of the part played by effective rainfall using a climatic station installed on the site.

The results are already very significant even now, and for objective 2 they are more or less definite. As we expected, this two years programme needs to be continued in depth for objective 3, and it is fortunate that Teslec will be succeeded by the Newtech programme, which will extend this research.

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