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# ANALYSIS OF THE GENESIS AND EVOLUTION OF *CALANCO* MORPHOLOGY IN AN EXPERIMENTAL AREA OF PAICCIA (RADICOFANI, SIENA, ITALY)

ABSTRACT: COLICA A., *Analysis of the genesis and evolution of calanco morphology in an experimental area of Paiccia (Radicofani, Siena, Italy).* (IT ISSN 0391-9838, 2000).

A study of *calanco* morphology in the area of Paiccia (Radicofani, Siena, Italy) was conducted in the period 1989-1996, based on the evaluation of the geological, morphological, pedological, tectonic and climatic aspects. The data collected, along with the examination of the *calanco* morphology, carried out by a series of photographic surveys, have clearly indicated that a *calanco* is formed by dynamic landforms such as rills, gullies, crowns and mudflows. The analysis of the evolution of these landforms allowed us to identify the self-feeding and genesis mechanisms of the *calanco* morphology. The self-feeding is essentially related to the development of these landforms. The development in turn is mainly linked to the climatic conditions and to the presence of perched watertables. The genesis seems to be due to the evolution of the rill hydrographic pattern.

KEY WORDS: *Calanco*, Mudflow, Crown, Gully, Rill, Tuscany (Italy).

RIASSUNTO: COLICA A., *Analisi della genesi ed evoluzione della morfologia calanchiva nell'area sperimentale di Paiccia (Radicofani, Siena, Italia).* (IT ISSN 0391-9838, 2000).

In questo articolo vengono presentati i risultati di un'analisi condotta, nell'arco di tempo compreso fra il 1989 e il 1996, su alcuni bacini calanchivi presenti in località Paiccia (Radicofani, Siena). Nell'area sono stati eseguiti studi geologici, pedologici, tettonici, climatici e morfologici, quest'ultimi anche mediante una serie di riprese fotografiche. Dai dati ottenuti si è evidenziato che la morfologia calanchiva è costituita da forme dinamiche quali i rivoli (*rills*), i fossi (*gullies*) e le colate di fango (*mudflows*). L'analisi dell'evoluzione di tali forme ha permesso di individuare i meccanismi di conservazione e di genesi dei calanchi stessi. La conservazione è legata allo sviluppo di queste forme dinamiche, a loro volta condizionate dall'andamento climatico e dalla presenza di falde d'acqua sospese (*perched watertables*). Per quanto concerne invece la genesi della morfologia calanchiva questa sembra essere dovuta principalmente all'evoluzione del reticolo idrografico dei rivoli.

TERMINI CHIAVE: Calanco, Colata di fango, Coronamento, Fosso, Rivolo, Toscana.

## INTRODUCTION

The *calanco* is a complex morphology for which there is no unequivocal definition as yet: a form of intense erosion which is found mainly in Italy in the Pliocene and Pleistocene clayey marine bedrocks, characterised by a series of small valleys with incisions with dendritic or subparallel patterns (Vittorini, 1977); heavily dissected terrain with steep, bare slopes and channels which rapidly incise and extend headwards, but which are frequently obliterated by mass-movement debris (Alexander, 1982); a hydrographic unit, of various sizes, with a horseshoe-like head area and comprising a system of tributary catchments separated by more or less sharp and steep divides, determined by the physical-mechanical characteristics of the bedrock (Mazzanti & Rodolfi, 1988; Moretti & Rodolfi, 2000 - in press); a part of landform with well-developed drainage networks formed by surface processes, especially rillwash, gullying and frequent shallow landsliding on very steep slopes (Torri & Bryan, 1997).

The headward retreat of *calanchi* has often caused problems, due to the interference with human activity. We have examples in Civita di Bagnoregio (Lazio) and Pisticci (Basilicata), where *calanchi* have isolated and damaged towns situated at the top of the slopes. In less important areas they have destroyed roads and railway and electricity lines. In order to limit this damage we have tried to understand the genesis of this landform which is widespread in

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Italy(1) and is also to be found in some areas of the Mediterranean basin, in America and in Asia. This genesis is still debatable. Losacco (1963) and Vittorini (1977), on the basis of studies in the Val d'Orcia area (Toscana), and Alexander (1982), after studies performed on the *calanchi* in Basilicata, believe that their genesis is due mainly to the rapid erosion caused by channels which deepen and retreat upwards, thus giving rise to small valley systems. According to Vittorini (1971) the genesis of *calanchi* in Val d'Era (Toscana) is linked to the slope aspect. These slopes present a discontinuous erosion which affects a considerable thickness of soil. Sfalanga & *alii* (1974) believe that the southern exposure is fundamental in the case of the *calanchi* in Val d'Era and Val d'Elsa areas (Tuscany). The low water contents along these *calanchi* (minimum contents 4,5% in the clays) allow rather high residual internal friction angles (up to maximum values of about 75°). Sdao & *alii* (1984) maintain the genesis of *calanchi* in Calabria is linked to the predominant western exposure and the coarse texture. Rodolfi & Frascati (1979) single out two *calanchi* forms in Val d'Era. These differ from the point of view of nature of the dominant morphogenetic process, which is influenced in turn, as Sfalanga & Vannucci (1975) had already noted, by lithological composition of substrata (a concept to be taken up by Pinna & Vittorini, 1989) and by the characteristics of the soils which develop there: the type A *calanco*, with higher sand and silt content in the bedrock, have a dense drainage pattern with small, narrow, deep valleys and «knife edged» divides, the dominant process is erosion by concentrated water; the type B *calanco*; the bedrock contains more clay, the divides have a steep, but not sharp, profile which separate relatively wide small valleys with concave bottoms, the dominant process is mudflow. In Val d'Era, Lulli (1974) suggests that the *calanco* genesis is linked to slope angle, which can remain steep if bedrocks with greater resistance are present as «cap-rock» on the top of the slope, e.g. beds of molasses. According to Guasparri (1978), the *calanchi* in the Siena basin (Tuscany) were formed both as result of sandy coverings at the top of the slopes and of the concentrated rilling action. Guerricchio & Melidoro (1979, 1982) believe that the *calanchi* in Lucania were formed by neotectonic fissuring and paleolandslides. Dramis & *alii* (1982) link the genesis of the *calanchi* in the Marche region to the climatic improvement of the Holocene period which favoured the development of linear incision. Centamore & *alii* (1980) suggest that *calanchi* in the same area may be due to both climatic change and neotectonic uplift which started in the Pleistocene. According to Dramis & *alii* (1982) deforestation on the slopes in the Marche in the past would have contributed to rapid expansion of *calanchi* forms. Calvo & *alii* (1991) ascribe the *calanchi* in south east Spain (Murcia, Almeria, Alicante and Valencia) to the lithology (easily erodible shales and marly clays), the high relief, neotectonics, the climate, the plant cover and the human activity. On the basis of studies carried out on Tuscany *calanchi* (Botro dell'Arpino, areas around Asciano, Rapolano and Radicofani) and ones in Lazio (Civita di Bagnoregio) and in the Romagna (Brisighella) Torri & Monaci (1991) have put forward the hypothesis that the evolution of these forms is linked mainly to surface landslides which affect thicknesses of weathered material of around 15-20 cm.

The present study was carried out in an attempt to provide data which clarify the genesis and self-feeding of calanco morphology.

## DESCRIPTION OF THE EXPERIMENTAL AREA

The study was conducted in Paiccia, Southern Tuscany, in the province of Siena (fig. 1a), 6 km N of Radicofani (F.129 S. Fiora, tav. I NW).

This area was chosen for various reasons: 1 - it is affected by erosive phenomena and still active processes, 2 - the *calanco* typology is representative of the morphology of the area of Radicofani, 3 - the *calanchi* forms are typical of the ones which develop in the Pliocene and Plio-Pleistocene bedrock in the neighbouring areas along the entire length of the piedmont zone of the Apennine chain.

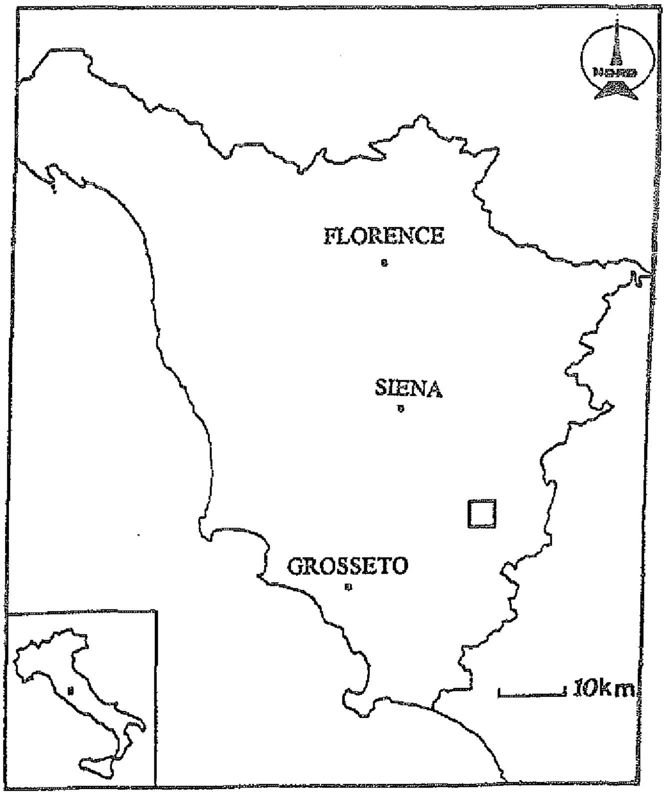

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FIG. 1a - The study area of Paiccia is indicated by a square (lat. 42°58'26" N and long. 0°43'32" W ref. Rome - M. Mario).

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(1) Piedmont, Liguria, Trentino, Emilia Romagna, Tuscany, Umbria, Abruzzi, Basilicata, Calabria and Sicily.

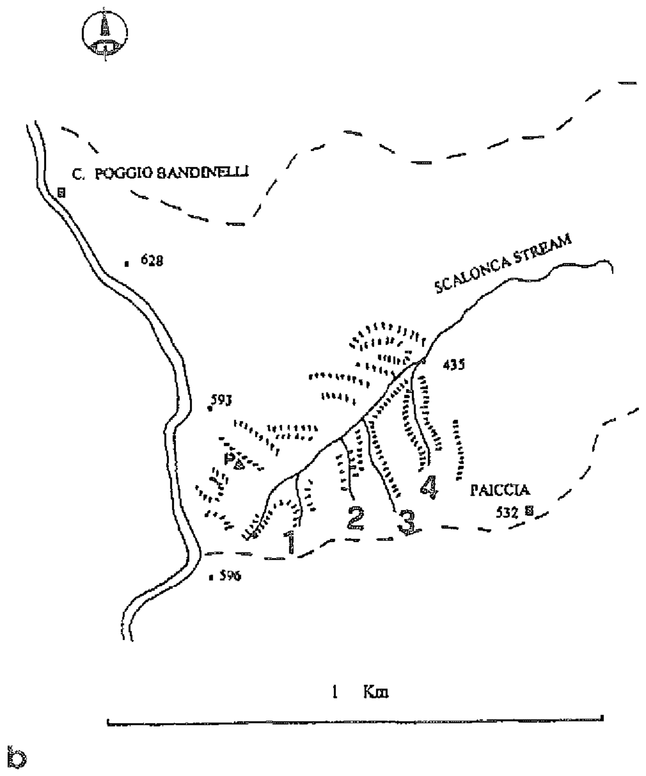

FIG. 1b - The four *calanchi* (1, 2, 3, 4) of Paiccia in the Scalonca stream basin (dashed line). P = point of view.

The study area, which extends over a surface of 155.000 m$^2$, is characterised by four *calanchi* (1, 2, 3, 4 in fig. 1b) which have developed on the N-NNW slopes whose retreating head is affecting the subhorizontal summit stretch (which extends from the head of the *calanchi* to the watershed of the Scalonca stream).

The substratum is formed by Pliocene marine bedrocks with strike N45 and dip 40NW. The stratigraphic sequence is formed by 54 layers ranging in thickness from 4 cm (levels) to 25 m (banks), as shown in fig. 2a. The texture varying from clay to sandy-loam (fig. 2b); gravels are present in conglomerate banks.

Parallel fractures, sets of joints, with oxidized borders and a vertical or subvertical direction, with a maximum depth of 10 m, have been identified: N60 and N20 which are coeval since they mutually intersect, and N120. In other *calanco* areas in Italy (Colica, 1986; Colica & Guasparri, 1990; Brondi & *alii*, 1992; Colica, 1992; Benvegnu & *alii*, 1993; Busoni & *alii*, 1998) as well as in Spain (Soriano & *alii*, 1992; Colica & *alii*, 1993), joints, the borders of which are oxidized to varying degrees, always occur. They appear to influence the morphogenetic process by creating «structural weaknesses» which favour water penetration.

*Calanco* morphology develops on steeper slopes (fig. 3), particularly from 435 m a.s.l., where the Scalonca stream flows, giving the local base level, up to about 513 m. It has a mean gradient of 24° but can exceed 50°. From 513 m to 532 m there is a flat surface, covered by a thin soil, with an average slope of about 14°.

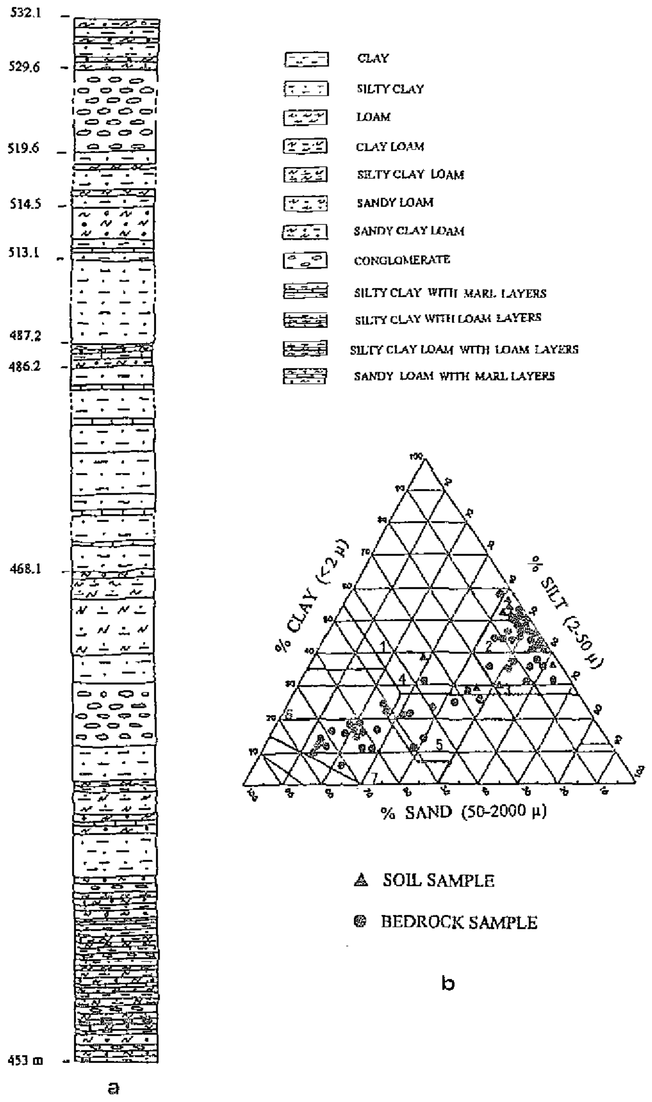

FIG. 2 - a) Stratigraphic column of the study area; b) Texture of bedrocks and soil horizons (after U.S.D.A., 1995); 1) clay; 2) silty clay; 3) silty clay loam; 4) clay loam; 5) loam; 6) sandy clay loam; 7) sandy loam.

*Calanco* are separated by relatively sharp divides, and form small hydrographic catchments. The axis of the latter consists of a «main gully», averaging 2 m in width and one metre in depth (fig. 4). The tributaries are represented by «secondary gullies» of smaller dimensions and by rills. These rills, with an average width of less than 10 cm and a depth of a few centimetres, lead the waters directly into the gully$^{(2)}$. While gullies are «permanent» landforms, rills

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(2) The terms rill and gully have been used according to the definitions of BERGSMA & *alii* (1996).

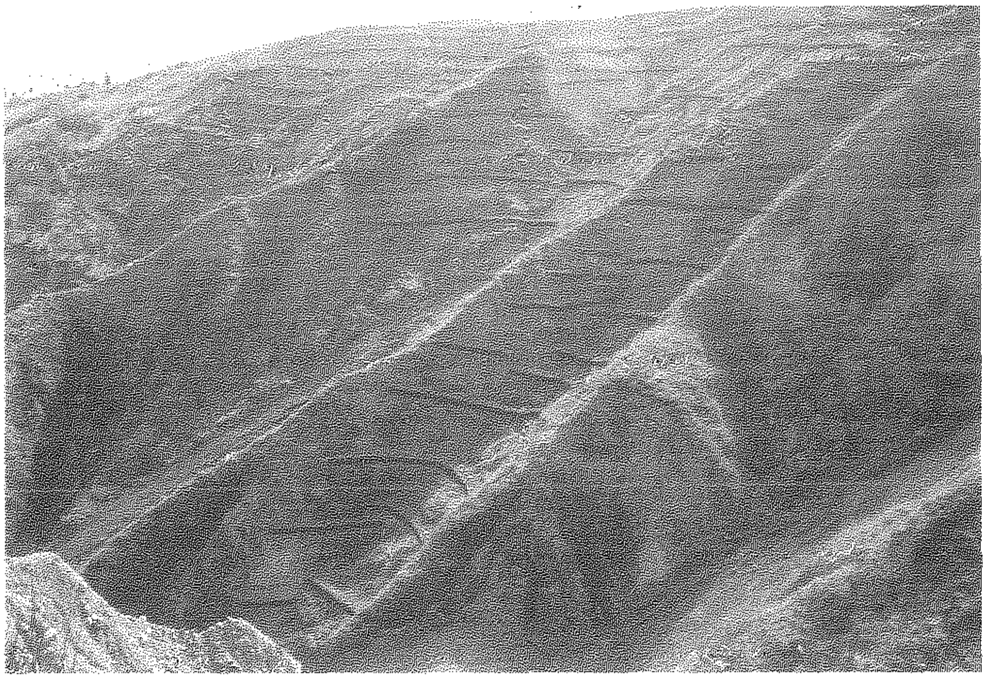

FIG. 3 - The four *calanchi* in the Paiccia area (February 1989). The horizontal elements are erosion control practices: *graticciate*.

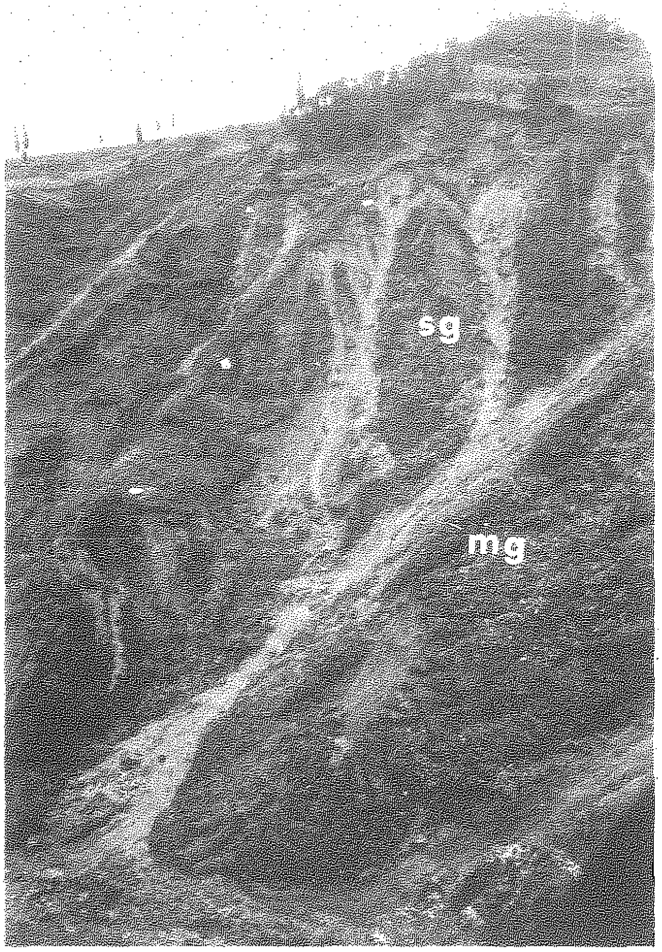

FIG. 4 - Main (mg) and secondary (sg) gullies.

may be «ephemeral» (Schumm & Lusby, 1963; Gerits & *alii*, 1987; Dietrich & Dunne, 1993), those which are erased by mudflows and splash erosion, or «permanent», the ones with tracks which remain marked throughout the season. The latter seem to be linked to more continuous water flow, after rainfall, due to the presence of perched watertables which causes water emergence during rainier months.

Other morphologies can be found in each catchment, including crowns (head scarps), sliding surfaces and mudflow accumulations (or accumulation lobes according to Landslide Recognition: Identification, Movement and Courses, 1996). Crowns are generally arch-shaped and vary in size; scarps are 40-60 centimetres in height, with gradients ranging from 54° to vertical, and they occur throughout the entire soil profile. Crowns are either located close to the top of the *calanco* slopes or along the slope between the main gully and the closest divide, and are generally parallel or subparallel to the divides. Sliding surfaces are generally smooth or lightly concave and vary in size (even more than one meter in width); the material coming from the scarp flows into them and can be deposited either in the immediate vicinity of the scarp, along the sliding surfaces, in the gullies or in the Scalonca stream.

Some soil horizons have developed on the surface at the top of the *calanchi* and on the slopes where the gradient is gentler. According to the classification of the U.S.D.A. Soil Taxonomy (1975), they are Typic Xerorthents. Two representative soil profiles were chosen for the study area. The first developed on a silty-clay bedrock, and the second on a silty-clay-loam one. In the first profile, silty-clays are present in all the horizons (A, C1, C2, Cr), while in the second there is a textural alternation between silty-clay-loam in the A horizon, clay-loam in AC and 2C and silty-clay-loam in 3C(5).

### Climate

The climate was characterised using rainfall data from the meteorological stations of Contignano, Pod. Pianotta, San Piero in Campo and Radicofani, and temperature data from Contignano and Pod. Pianotta. In particular, for the period 1989-1996, when this research was conducted, the average annual rainfall amounted to 757 mm, while the maximum intensity of daily rainfall was 42 mm. The average annual temperature was 16° C; with minimum in January of 4°C and maximum in July of 24°C. According to Thornthwaite's classification (1948) the climate is humid-subhumid, first mesothermic ($C_2B_1$'); with seasonal variations of $S_2$ type: severe water deficit in summer ($Ia > 33,3$) and excessive water in winter ($Ih > 20$), thermic summer concentration ($a' < 48\%$). A humid period in November and December alternates with a subarid phase from June to August, with two hot-humid transitions limited to May and September. The climate can therefore be considered as *subtropical*, with an almost completely arid summer (*Mediterranean*) and with rainfall concentrated in the colder months. The periods of water surplus (S), utilization (U), deficit (D) and recharge (R) in the soil are shown in fig. 5.

### Erosion Control Practices

At the beginning of 1989, erosion control practice «*graticciate*» (small fences) were introduced along the three more eastern *calanchi* (fig. 3). The *graticciate*, consisting of chestnut stakes fixed in the ground and connected by smaller transverse stakes of the same material, were placed perpendicularly on the steeper areas, at 5-10 m intervals, usually extending laterally for about 10 m.

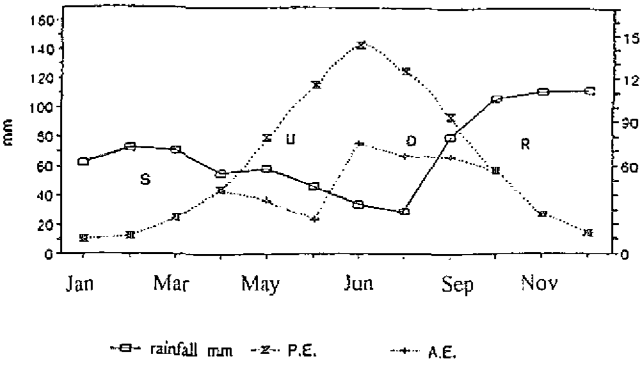

FIG. 5 - Diagram of the hydric balance (1954-1996).

## METHODOLOGY

*Calanco* materials were characterised by particle size analysis, chemical (C.E.C., E.S.P., pH and conductivity), porosity and consistency limit (Atterberg) analyses, following standard methodologies (Colica, 1992). Particle size analyses were conducted on all bedrock samples, while chemical, porosimetric and consistency limits analyses were only performed on a selection of samples. For each soil horizon the sampling was conducted with the aim of determining each of the above mentioned characteristics.

### Photographic Surveys

Photographic surveys were carried out from a fixed position (P in fig. 1b) located on the opposite slope to analyse the temporal evolution of the four *calanchi* slopes. The average distance from this point to the experimental area is around 200 m. The first photographic survey was carried out in February 1989 by G. Rodolfi, who took the initial pictures available. It was therefore possible to carry out the analysis from February 1989 until November 1996. The evolution of the slopes has also involved the *graticciate*. Since they were constructed in February 1989, these *graticciate* have been subjected to erosion and have been deformed or, in some cases, totally destroyed.

## RESULTS

### Factors Influencing the Triggering of the Dynamic Landforms

Several factors in the area seem to contribute to *calanchi* erosion. These include slope gradient, differences in the chemical-physical behaviour of soil and bedrock, the textural alternation of the bedrocks and the climate.

In some places, it is possible to have slope angles which exceed the internal friction angle of the bedrock and soil (values obtained with Gibson's relationship, 1953, tab. 1 and tab. 2); so that instability conditions are created. The data in tab. 1 and tab. 2 show lower E.S.P. values close to the surface, indicating leaching by infiltrating water. Sodi-

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(5) A - 0-7 cm depth, colour 2,5Y5/1 (Munsell Chart, 1995), strong fine subangular blocky, fine cracks (2-30 cm depth), $CaCO_3$ >10% (determined with HCl), biological activity, fine roots.
C1 - 7-40 cm, colour 2,5Y5/1, fine to medium subangular blocky, fine cracks, $CaCO_3$ >10%, biological activity, rare fine roots.
C2 - 40-60 cm, colour 2,5Y5/2, massive, $CaCO_3$ >10%, Fe and Mn nodules, rare biological activity, rare fine roots.
Cr > 60 cm, colour 5Y4/1, massive, $CaCO_3$ >10%, Fe and Mn nodules, very rare biological activity.
A - 0-7 cm, colour 2,5Y5/1, strong fine subangular blocky, fine cracks (3-30 cm depth), $CaCO_3$ >10%, strong biological activity, fine to medium roots.
AC - 7-40 cm, colour 2,5Y4/2, medium subangular blocky, fine cracks, $CaCO_3$ >10%, Fe and Mn nodules, biological activity, rare fine and very fine roots.
2C - 40-55 cm, colour 2,5Y4/2, medium subangular blocky, $CaCO_3$ >10%, many Fe and Mn nodules, horizontal roots along the 2C-3C contact surface.
3C >55 cm, colour 2,5Y5/4, massive, $CaCO_3$ >10%, rare biological activity, very rare fine roots.

TABLE 1 - Apparent density, porosity, plastic and liquid limits, index of plasticity, C.E.C., E.S.P., pH (these last three values are obtained from the saturated extracts) and internal friction angle (Φ) of the selected samples of bedrocks

| BEDROCK | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Density (g/cm$^3$) | 21.5 | 2.13 | 2.21 | 2.1 | 1.76 | 2.17 | 2.29 | 2.14 | 2.2 | 2.22 | 2.41 |
| Porosity < 100 µm % | 17.3 | 18.4 | 16.9 | 18.1 | 25.9 | 18.1 | 10.6 | 22.6 | 16.6 | 18.5 | 10.6 |
| Plastic Limit | 20.4 | 25.8 | 27.2 | 18.7 | 20.4 | 17.3 | 17.2 | 13.7 | 13.6 | 14.4 | 11.8 |
| Liquid Limit | 40.1 | 51.1 | 40.3 | 47.2 | 23.7 | 22.2 | 22.3 | 24.5 | 26.2 | 21.1 | 32.3 |
| Plastic Index | 19.7 | 25.3 | 13.1 | 28.5 | 3.3 | 4.9 | 5.1 | 10.8 | 12.6 | 6.7 | 20.5 |
| C.E.C. (eq/100g) | 11.2 | 13.6 | 12.4 | 12 | 4.3 | 9.2 | 7.2 | 3.6 | 4 | 9.6 | 8 |
| E.S.P. % | 37.5 | 13.3 | 78.7 | 52.8 | 30.8 | 43.4 | 30.5 | 8.8 | 12.6 | 46.4 | 29 |
| p.H. | 7.3 | 8.2 | 7.4 | 7.9 | 7.2 | 7.4 | 8.2 | 7.2 | 7.4 | 7.4 | 7.7 |
| Φ | 24 | 20.1 | 26 | 20 | 29 | 28 | 27.5 | 26 | 25.5 | 27 | 22 |

TABLE 2 - Apparent density, porosity, plastic and liquid limits, index of plasticity, C.E.C., E.S.P., pH (these last three values are obtained from the saturated extracts) and internal friction angle (Φ) of the samples of soil

| SOIL HORIZON | A | C1 | C2 | Cr | A | AC | 2C | 3C |
|---|---|---|---|---|---|---|---|---|
| Density (g/cm$^3$) | 1.44 | 1.51 | 1.5 | 1.8 | 1.3 | 1.23 | 1.5 | 2.1 |
| Porosity< 100 µm % | 30.3 | 30 | 30 | 27.2 | 31.5 | 31.7 | 30.1 | 24.6 |
| Plastic Limit | 25.4 | 24.7 | 20.2 | 13.7 | 18.8 | 22.4 | 17.3 | 27.7 |
| Liquid Limit | 49.1 | 50.2 | 25.3 | 27.2 | 24.3 | 28.4 | 27.4 | 40.5 |
| Plastic Index | 23.7 | 25.5 | 5.1 | 13.5 | 5.5 | 6.1 | 10.1 | 12.8 |
| C.E.C. (eq/100g) | 15.2 | 14.4 | 10.8 | 10.4 | 16.4 | 16 | 7.6 | 13.2 |
| E.S.P. % | 2.7 | 21 | 22 | 22 | 3 | 7 | 10.5 | 27 |
| p.H. | 7.6 | 8 | 8.1 | 8.1 | 7.6 | 7.9 | 7.9 | 7.9 |
| Φ | 21 | 22.5 | 27.8 | 25 | 27.3 | 27.2 | 26.3 | 25 |

um accumulates in the perched watertables at the contact between the soil and the parent material, producing conditions favoured for clay dispersion (Rengasamy & Olsson, 1991). So, the conditions for the formation of shallow mass movements (mudflows) are favoured, principally during the high rainfall period (see fig. 5).

Along the slopes there are several layers of conglomerates of varying thickness, from a few decimetres to metres. The presence of bedrocks with lower permeability, such as silty-clays or silty-clay-loam, below the conglomerates, causes the formation of small perched watertables in the conglomerates, especially after heavy rainfalls. This was shown by seepage water and small springs observed during such periods. This water can contribute to the formation of both rills and mudflows.

### *Evolution of Dynamic Landforms*

*Calanco* morphology is formed by a series of dynamic landforms such as rills, gullies, crowns and mudflow accumulations. The analysis of this morphology was conducted with the aid of a series of 14 photographic surveys carried out over a period of 94 months (February 1989 - November 1996). The drawings in fig. 6 a, b, c were derived from the photographic sequences[4]. In order to demonstrate the evolution of the *calanchi* slopes more clearly, only three of the periods are shown, i.e.: February 1989, November 1992 and November 1996.

*February 1989* (fig. 6 a) - Few, and extremely limited, crowns are present: one at the bottom of the first *calanco*; four in the second, two at the bottom and two near the top; and one at the bottom of the third. There are some small mudflow accumulations: two in the first *calanco*; three in the third; and one in the fourth. The crowns producing them are not visible, because they were formed several months before the date of the photographic survey and the small crowns were most probably remodelled by erosion. Rills are clearly visible in the first and third *calanco;* they generally present a hydrographic pattern with a weak hierarchized organisation. The same phenomenon has been observed in Val d'Era by Mazzanti & Rodolfi (1989). The sliding surfaces are zones of erosion and of partial deposition. In fact, in the area where the mudflow mass has just passed, a layer of mud (*patina*) is left, the thickness of which varies from just a few mm (at the foot of the scarp) to a few dm (some metres after the scarp). The crowns have been remodelled and the sliding surfaces have been located through the «*patina*». Following interviews with local inhabitants, it was ascertained that the construction of the *graticciate* along the slopes had finished about a month before.

*During the successive 47 months* - The most significant development of the crowns occurs; they tend to rise either towards the lateral divides close by or towards the summit of the *calanchi*. In the rainier months, more mudflows and

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[4] Gullies have not been traced out in fig. 6, in order to facilitate the interpretation of the drawings. The development of the gullies is illustrated in fig. 10.

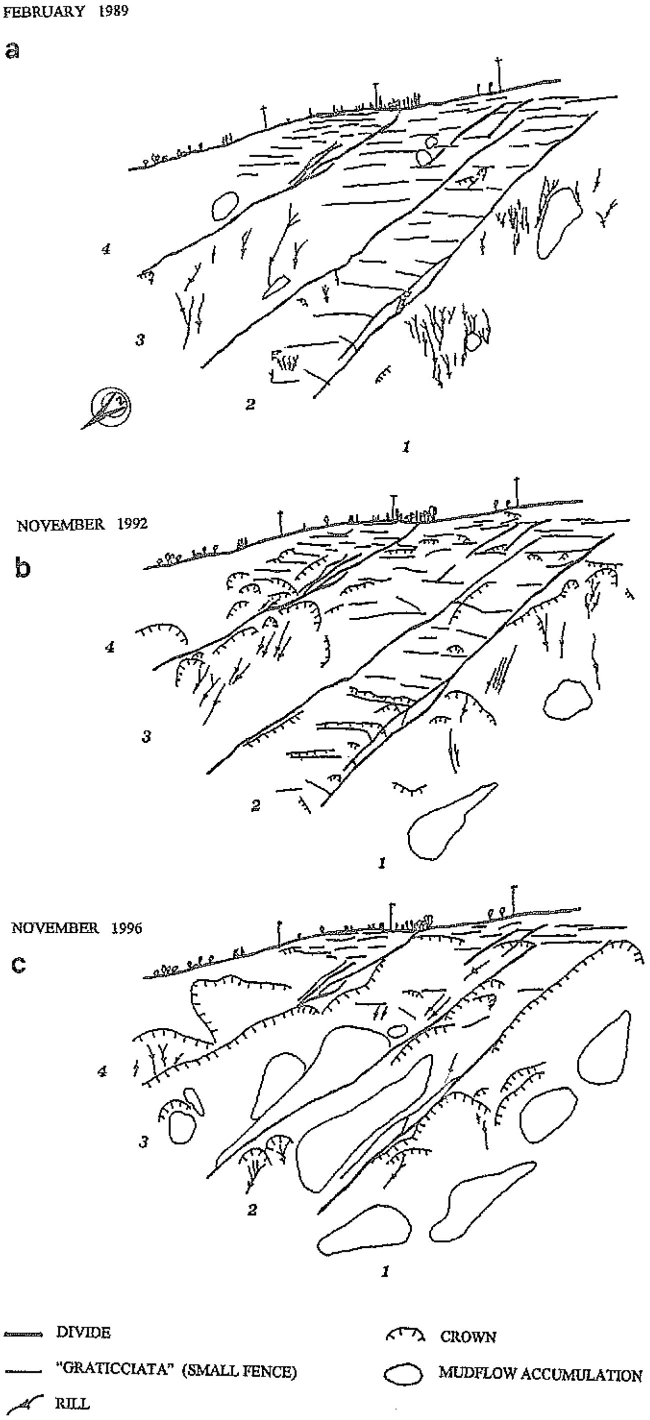


FIG. 6 - Evolution of the dymamic landforms in the four *calanchi*.

rills can be observed. The mudflows are present on all the slopes and assume greater dimensions. This phenomenon was also observed in Val d'Era by Rodolfi & Frascati (1979). In the first valley, the access routes for the construction machinery used for the dams on the Scalonca stream (built in February 1989) became the preferential course for these mudflows. The mudflow accumulations move on sliding surfaces and in the presence of similar slope gradient and natural water contents, the following situations can be observed:

- if the mass in motion is small (less than a metre in width, fig. 7 a) it accumulates at the foot of the scarp without moving further downslope;
- if the mass is larger, (from about one metre to 3 m, fig. 7 b) it flows downslope and when it comes across areas even sporadically covered by vegetation or by a rougher substratum, it tends to stop after a maximum of about ten metres;
- an even larger mass (more than 3 m, fig. 7 c, d), regardless of the roughness of the surface over which it flows, reaches the nearest gully and flows towards the stream;

In several cases, a sliding surface can become a gully (secondary or main).

If the accumulation, regardless of its dimensions, intercepts a pre-existing sliding surface or a gully, may change direction of motion and follows this way towards the main gully and the stream (fig. 7 e, f) or directly towards the stream.

In the soil which is more porous than the underlying bedrock, and in the bedrock itself where the more porous bedrock strata, such as conglomerates, are to be found, perched watertables can develop. Some perched watertables can be fed through cracks caused by pedogenesis, desiccation cracks and joints. The perched watertables can cause small springs which allow the formation of rills. On the sliding surfaces, permanent rills, which are not erased by successive rain or by other mudflows, evolve hierarchically and take on a dendritic pattern.

If a mudflow encounters a *graticciata*, it stops and accumulates. As soon as the stake is sufficiently shifted from its original position, water percolates into the hole containing the stake. The water has a lubricating effect that further weakes the frictional resistance between the stake surface and the soil. With the increasing weight of the accumulated bedrock, the *graticciata* deforms progressively, and it may be totally removed.

*November 1992* - The retreat of the erosive phenomena towards the divides is shown in fig. 6 b. Many crowns have grown, moving in the direction of the divides in every *calanco*. The area affected by the deformation of the *graticciate* also appears more extensive towards the divides. In the eastern *calanchi* some *graticciate* have been deformed or totally removed by the mudflows. At the beginning of the rainy period, new accumulations are already visible (first *calanco*) and rills appear (most of all in the first and third *calanco*, where perched watertables are present in the bedrocks) on the sliding surfaces.

*During the successive 44 months* - The retreating crowns have proceeded towards the divides. The area delimited by the deformed *graticciate* is more extensive towards the top. In the rainier months, the mudflows grow. In the same periods the rills seem to be well developed (most of all in the first and third *calanco*). Two situations should be highlighted, as they can explain the genesis of a *calanco*:

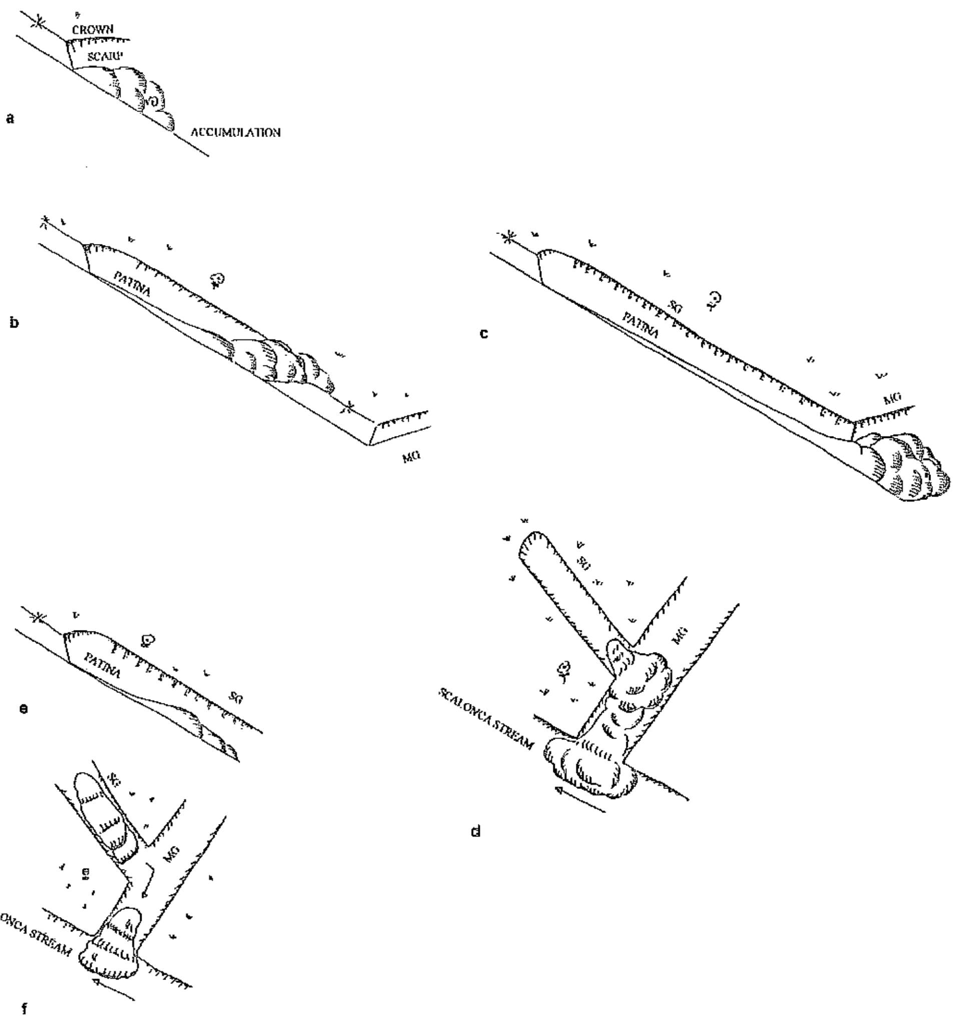


FIG. 7 - Kinds of evolution of a mudflow accumulation along a *calanco* slope. a) If the mass in motion is small (less than a metre in width) it accumulates at the foot of the scarp without moving further downslope; b) If the mass is larger, (from about one metre to 3 m) it flows downslope and when it comes across areas even sporadically covered by vegetation or by a rougher substratum, it tends to stop after a maximum of about ten metres; c), d) If the dimension of the accumulation is even greater (more than 3 m), regardless of the roughness of the surface over which it flows, it reaches the nearest gully and flows towards the stream; e), f) If the accumulation, regardless of its dimensions, intercepts a pre-existing sliding surface or gully, it changes direction of motion and follows this towards the main gully and the stream.

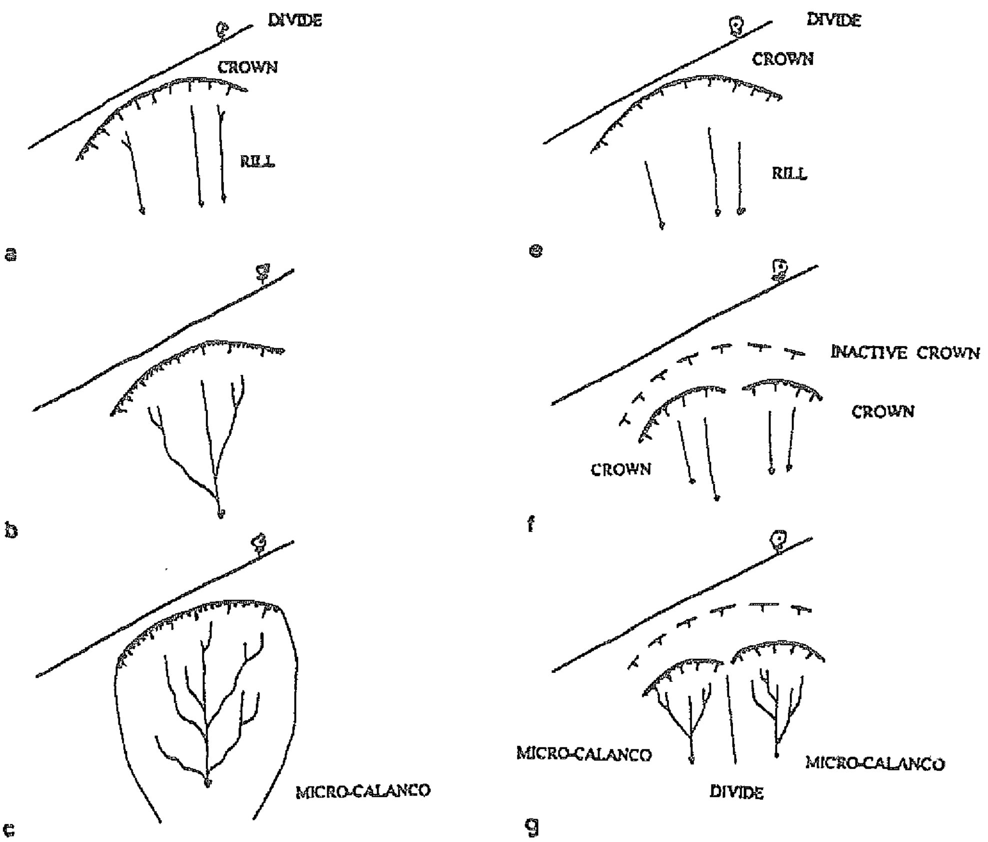
– if a crown is inactive, or at least does not retreat towards the divide, the rills on the sliding surface which have not been obliterated by heavy precipitation or by mudflows, develop a dendritic pattern as a result of the hierarchized organisation (fig. 8 a, b, c). This change involves a transition from an almost flat surface to a more concave one, due to the erosion of the hydrographic microcatchment which is being formed. The consequence of this morphological microvariation is the creation of a micro-*calanco* (fig. 8 c).

– in some cases secondary small crowns are formed on the sliding surface, between a big crown close to a divide and its accumulation at the foot of the slope on the sliding surface, parallel to the main crown. If crowns are inactive or do not retreat towards the divide, rills are formed and develop a hierarchized organisation (fig. 8 e, f, g) in every area delimited by a small crown and its accumulation. The sliding surfaces change from straight to almost straight and then concave, following the erosion caused by the incipient microcatchments. The hydrographic microcatchments are gradually formed, separated by secondary divides orthogonal to the direction of the main divide; micro-*calanchi* are being formed (fig. 8 g).

*November 1996* (fig. 6 c) - In the area surrounded by crowns almost all the *graticciate* have been destroyed. Large accumulations have increased towards the S (first, second and third *calanco*). On the sliding surfaces the rills are not very evident because this period precedes the maximum rainfall. The recently formed micro-*calanchi* have developed further (bottom of the second calanco).

The succession of phenomena which characterise the evolution of the *calanco* slopes can be summarized as follows:

FIG. 8 - Genesis of a micro-*calanco* (a, b, c). Genesis of two micro-*calanchi* (e, f, g).



- during the rainy periods, the natural water contents increase significantly in the soil horizons,

- meteoric and subsurface water, the latter also springs from the perched watertable (located in a higher position along the slope), infiltrates and accumulates in the soil-bedrock interface (fig. 9 a, b, c),

- once the soil is saturated, it collapses (fig. 9 d); if the conditions of water increase persist or the amount of rainfall is extremely great, or if the dimensions of the accumulation are sufficient to overcome the friction resistance of the underlying matter, a mudflow forms (material which can be weathered to varying degrees) and slides down on the bedrock (fig. 9 e),

- every mudflow erodes the area where it flows and can sometimes create a gully,

- the mudflow leaves a *patina* behind (fig. 9 e), similar to that of a «snail», few centimetres thick, which hinders the recognition of the underlying lithology (fig. 9 f); in some cases the persistence of this phenomenon, especially in the steeper slopes, has led to the total masking of the stratigraphic layers and of the original slope surface. Once a track is formed, paved by the *patina*, it can become a preferential flowing zone even for other mudflows, which do not necessarily have the same origin,

- the meteoric and subsurface water in the soil, the erosion at the foot of the scarp, caused by the water present along the soil-bedrock interface, and gravitational action favour the creation of a new scarp and relative crown upslope (fig. 9 f),

- the crowns advance towards the divide, and at the same time an enlargement in a perpendicular direction can be observed.

Within this succession of events extremely important situations can be observed: the genesis of a small *calanco* within another *calanco* is possible if the rills «survive» the other erosion phenomena (fig. 8).

On the basis of this succession of events it is possible to develop a hypothesis of the evolution of a *calanco* area (fig. 10 a, b).

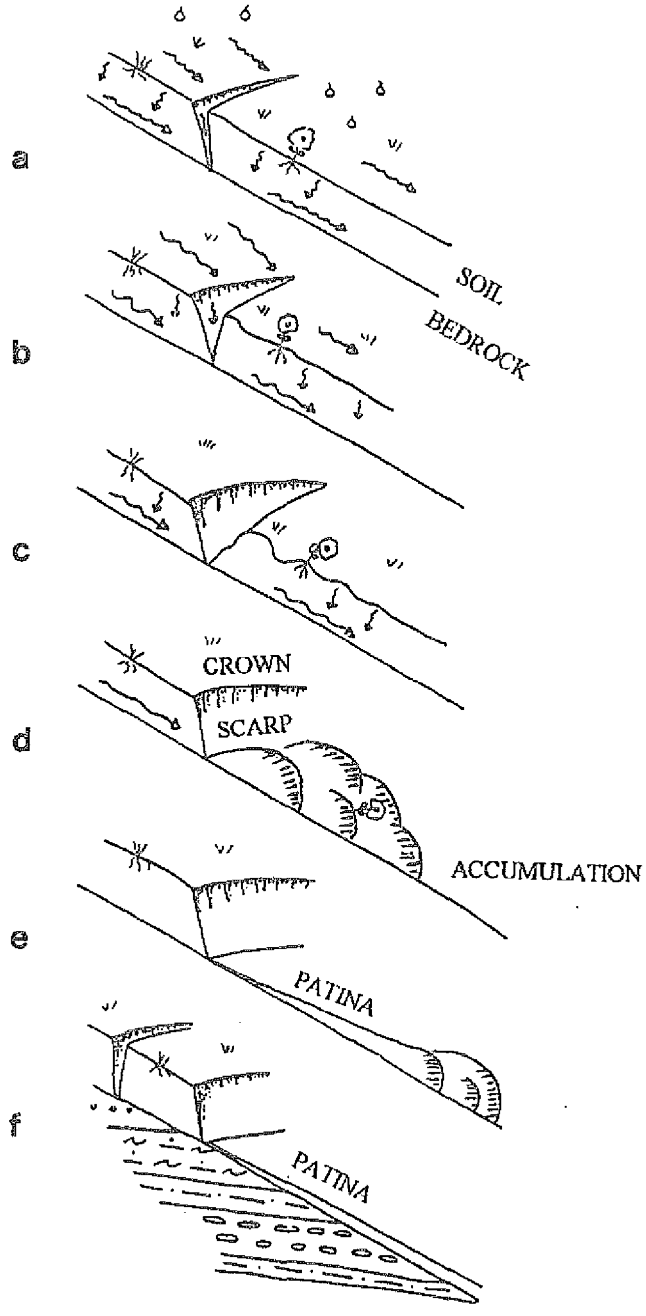


FIG. 9 - a-f) Genesis and evolution of the scarp, accumulation, sliding surface and *patina* of a mudflow along a *calanco* slope. The drawing «f» shows the *patina* hindering the recognition of the underlying lithology.

## CONCLUSIONS

The studies and analyses described in the article indicate that there are certain factors which favour the formation of *calanchi,*, such as:

– the high slope gradient,

– the different chemical-physical behaviour of soil and bedrock,

– the particular stratigraphic succession which leads to different permeability levels in layers and allows the formation of perched watertables,

– the presence of cracks and joints,

– the particular climatic conditions.

So, the following conclusion can be drawn:

1. the *calanco* is a particular morphology represented by a series of dynamic landforms such as gullies, rills, crowns and mudflows;

2. the development of the above mentioned landforms, which are responsible for the development of the *calanco* morphology, is not constant in time but influenced by the local climate. The growth takes place during the rainy months;

3. during this period perched watertables develop in the soil and in the more porous bedrocks such as conglomerates;

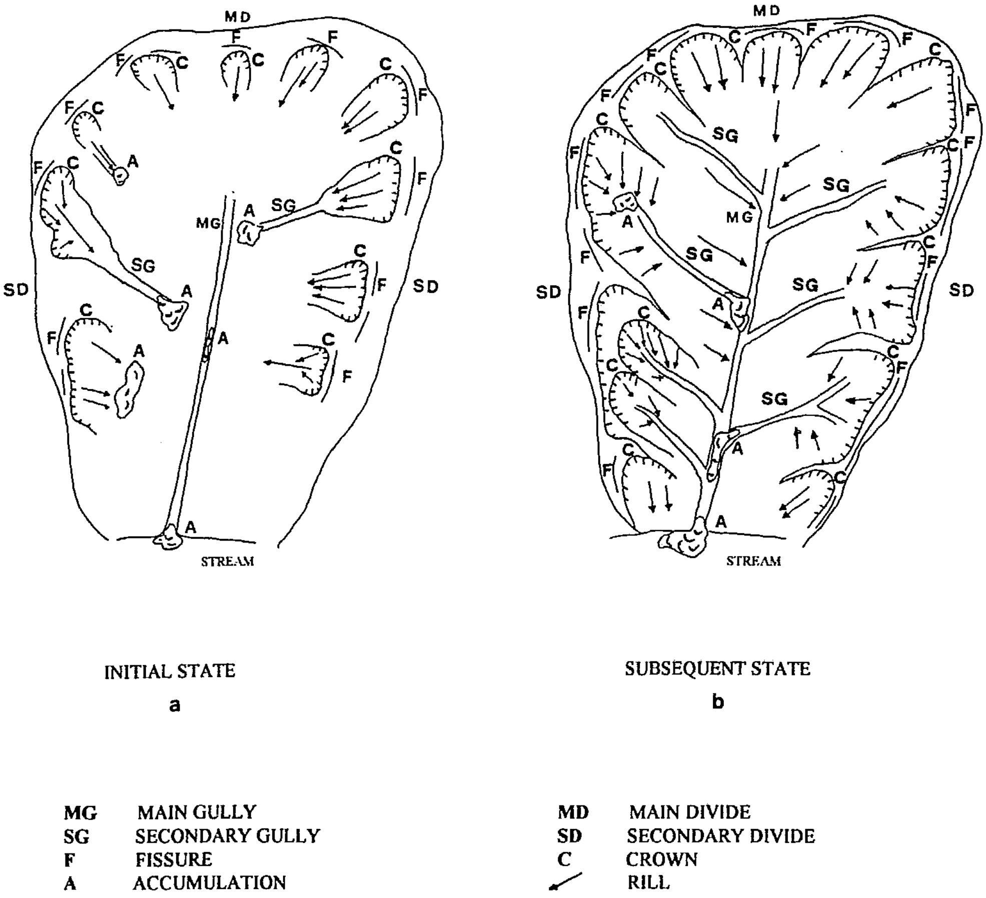
4. the meteoric and subsurface water can also be conveyed into the perched watertables through cracks and joints;

5. water springs from the perched watertables, thus causing the growth of rills;

6. the genesis of a *calanco* is due to permanent rills that evolve hierarchically and take on a dendritic pattern.

7. the erosion control practice *graticciate* (small fences) introduced along the *calanchi* have no durable effect, due to the lack of maintenance. In highly dynamic erosional landscapes, when erosional control practices are necessary, the use of *graticciate vive* (living fences) is advisable since these necessitate less continuous maintenance and cause a lower environmental impact.

FIG. 10 - a) Initial state of a *calanco*; b) Subsequent state of a *calanco*.



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