The May 5th, 1998, landsliding event in Campania (Southern Italy): inventory of slope movements in the Quindici area

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Multiple debris-flows in volcaniclastic materials mantling carbonate slopes

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ABSTRACT: On May 5, 1998, hundreds of rainfall-induced soil slide – debris flows originated in the Campania region of Southern Italy. The landslides, which involved volcaniclastic materials overlying a carbonate bedrock, moved with high velocity downvalley and invaded five towns located at the mountain foothills, and resulted in 160 casualties. This paper deals with the landslides that occurred in the Vallone Connola - Vallone S. Francesco drainage basins, upslope from the town of Quindici, on the northern slopes of Mount Pizzo d'Alvano: there, tens of shallow mass movements originated, which were responsible for the eleven victims at Quindici. After a description of the main geologic and geomorphologic features of the basins, the gravitational phenomena are dealt with by presenting a zonation of the landsliding areas. Particular emphasis is given to the stratigraphy in the landslide source areas and to the sedimentology of historic similar phenomena recorded in the fans stratigraphy at the mountain foothills.

1 INTRODUCTION

On May 5, 1998, a major slope-stability crisis struck the Campania region (Southern Italy), when a huge number of rainfall-induced landslides invaded five foothill towns, causing 160 deaths and about 100 million dollars in property losses. Eleven victims were recorded at Quindici, where the May 1998 event represented only the last episode in a long history of instabilities. The first documented instability event, in fact, dates from 1632 (Calcaterra et al. 2000); since then, many other hydrogeological disasters have been documented, up to the relatively recent episode occurring on January 1997. Nevertheless, the May 5, 1998, event has to be considered as unprecedented, both in terms of number of landslides triggered and the total volumes: more than 300 individual mass movements mobilized about 1,500,000 m^3 of material and spread out over about 8% of the municipal territory (Fig. 1). The landslides occurred as soil slides in volcaniclastic materials resting over carbonate bedrock, typically involving thickness on the order of 1-2 metres, and evolving in their downvalley movement into rapid to very rapid debris flows. The 1998 event at Quindici shares relevant features with many other similar slope movements that have affected the Campania region over the decades: soil slide-debris flows in the Campanian volcaniclastic soils, in fact, are being studied since the 1950s (Lazzari 1954, Civita & Lucini 1968, Civita et al. 1975, Guadagno 1991). After the last disaster, the interest of the scientific community and the public authorities increased. The 1998 slope movements have already been discussed in some recent notes (Del Prete et al. 1998, Calcaterra et al. 1999a, 2000), which mostly focused on the landslide inventory, and on analysis of the morphometric and geomorphologic features which controlled their occurrence; preliminary analyses of their triggering factors and mechanisms of instabilities have also been performed.

The present study deals with the Vallone Connola-Vallone S. Francesco area (Fig. 2), which lies upslope from the town of Quindici. The choice of the area was dictated by the following considerations: the landslides coming from these two valleys were responsible for the eleven casualties; both the frequency and the area of slope movements were the highest and largest registered among the basins upslope from the town, respectively; and, finally, a great amount of data, from the detachment areas to the zones of deposition, was collected in this sector in the weeks following the event.

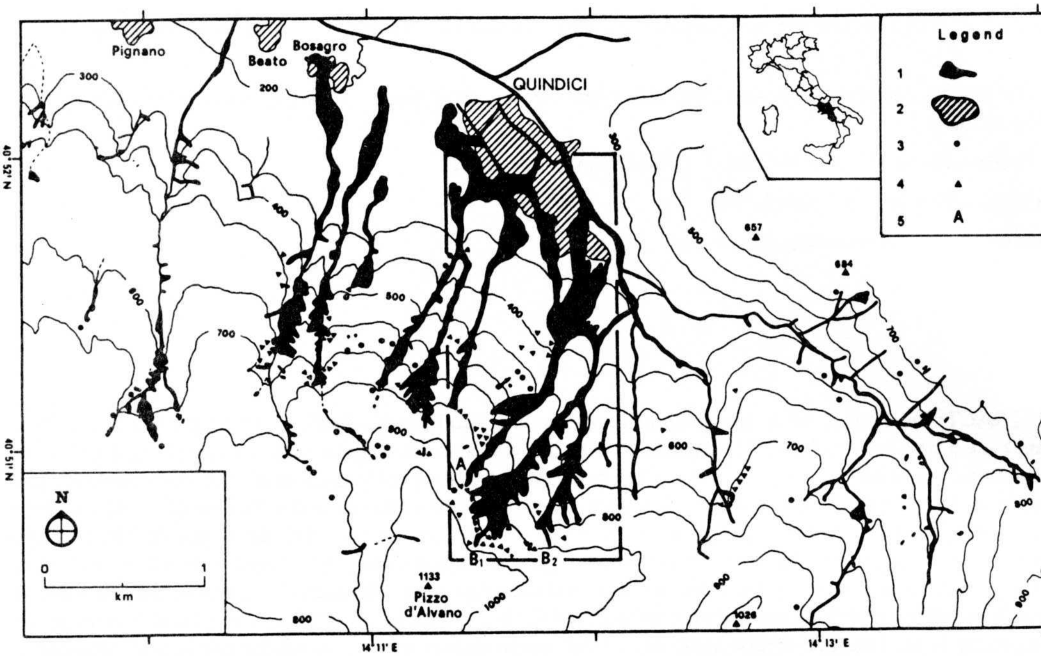

Figure 1. Distribution of slope failures during the May 5, 1998, event at Quindici (after Calcaterra et al. 1999a, modified). Legend: 1) Soil slide – debris flow; 2) Inhabited area; 3) Unmappable landslide; 4) Location of open cracks; 5) Identification of drainage basins (A = Vallone S. Francesco; B1 = Vallone Connola – left branch; B2 = Vallone Connola – right branch). The inset box refers to the study area of this report.

2 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

Vallone Connola and Vallone S. Francesco originate on the northern slope of Mount Pizzo d'Alvano (1133 m a.s.l), which is comprised of a Cretaceous to Tertiary carbonatic sequence, dominated by limestones. The carbonate bedrock, in turn, is overlain by volcaniclastic deposits erupted during Vesuvian and Phlegrean explosive activity. The morphology of Mt. Pizzo d'Alvano is essentially controlled by local tectonics and by the development of karst processes in the carbonate rock basement: the very steep and rectilinear deep valleys which dissect the massif follow primary tectonic lineations, while several closed depressions and flat areas, both at the summit of the mountain and on the slopes, are the main geomorphic results of karst activity. At several sites along the slopes, the presence of thick beds of limestone produces vertical cliffs which locally increase the local hillside steepness. Continuity of the morphology is, in addition, repeatedly broken by a large number of pathways which connect the roads in the valley with the summit plateau. The slopes, before the 1998 event, were almost entirely covered with a dense vegetation, dominated by hazelnut and chestnut trees.

Surveying of the thickness in the pyroclastic cover revealed the situation shown in Figure 2: pyroclastics mantle almost the entire study area, so that the bedrock exposures are practically confined to the subvertical carbonate cliffs. The highest thickness of pyroclastic deposits (from 5 m up to >20 m) were surveyed at Piani di Prata (a tectono-karst surface at the top of the mountain) and at the foothill area. The stratigraphic meaning of these deposits is definitely different: primary deposits are essentially found in the tectono-karst summit plateau and in other similarly smoothed surfaces in the upper reaches of the basins, while reworked sediments related to gravity-driven processes clearly prevail at lower elevations. The slopes are mostly covered by 1-5 m thick pyroclastics, while the <1 m-class was found on the steepest portions (a >30° sector) of the area, where many detachment areas of slope movements have been recognized.

Within the volcaniclastic sequence, the detailed stratigraphy was analyzed in selected sections (Fig. 3): this study led to the recognition of at least two eruptive events from Mount Vesuvius (which is located some 20 km west of the study area):

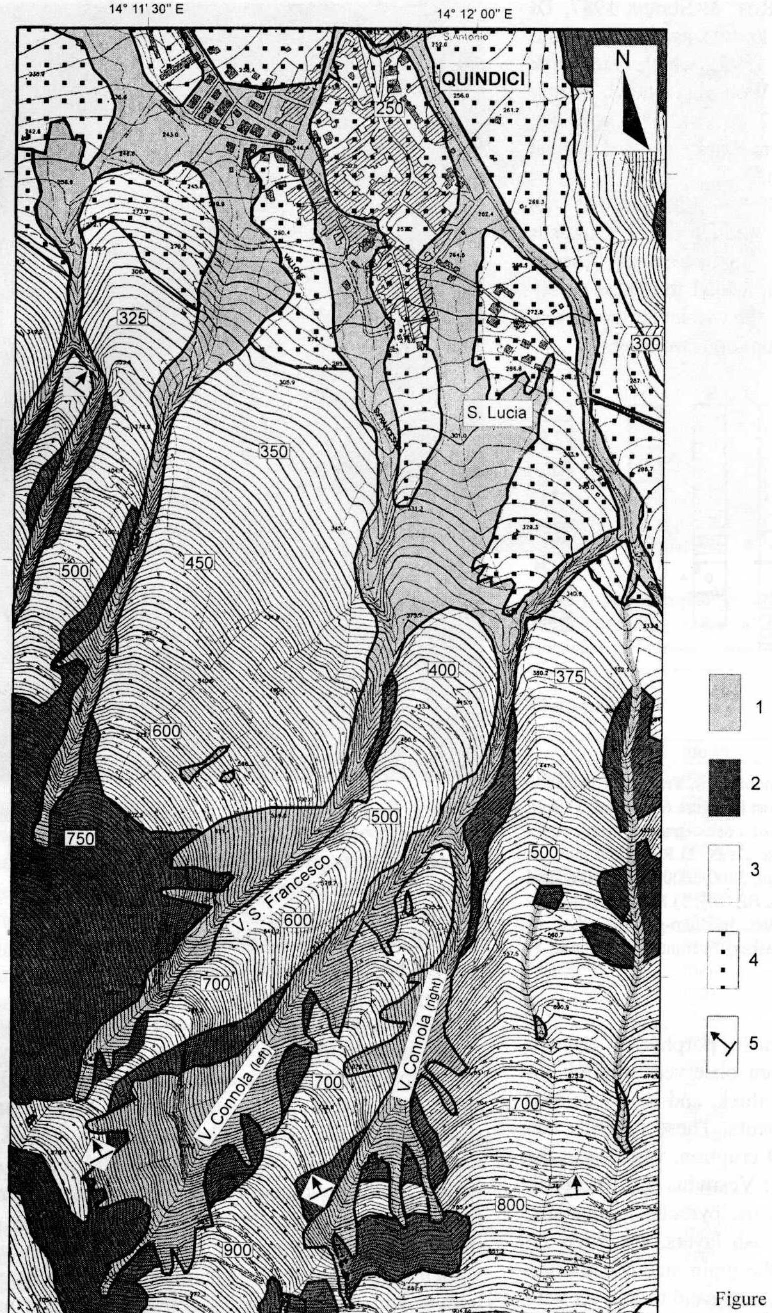

Figure 2. Landslide distribution and pyroclastic cover map of the Connola - S. Francesco area. Legend: 1) Soil slide - debris flow; 2) Thickness of the pyroclastic cover lower than 1 m; 3) Thickness of the pyroclastic cover ranging between 1 and 5 m; 4) Thickness of the pyroclastic cover greater than 5 m; 5) Attitude of carbonate beds.

- the Mercato eruption (Rosi & Sbrana 1987, Di Vito et al. 1998), also known as the Ottaviano eruption (Rolandi et al. 1993), which dates back to about 8000 yrs. BP. Well vesiculated, mostly aphiric, centimetric (1-2 cm) in size, white to grey pumice (80-100 cm thick) are the typical products of this eruption.
- the Avellino eruption (3900 – 3600 yrs. BP - Di Vito et al. 1998), whose stratigraphical marker is given by two levels of sanidine-crystal bearing, centimetric pumice, with a total thickness of 30-60 cm. In some sections, the two levels are mixed, thus testifying to post-eruption reworking.

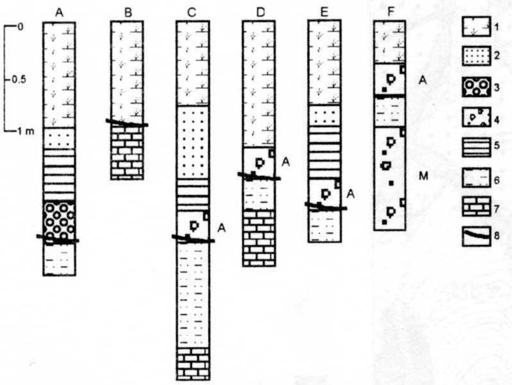

Figure 3. Stratigraphy of the Connola – S. Francesco landslide detachment areas. Location is shown in Figure 6. Legend: 1) Soil; 2) Reworked pyroclastics made of coarse-grained pumice and scoriæ, with subordinate carbonate clasts; 3) Reworked pumice; 4) Pumice of the Avellino eruption, 3900-3600 yrs. BP (A), and of the Mercato eruption, 8000 yrs. BP (M); 5) Reworked, locally rich of decomposed organic matter, medium-grained ashes; 6) Brown-yellowish, fine reworked ashes; 7) Jointed limestones; 8) Surface of rupture.

In addition, dark greenish, porphyritic angular scoriæ and lapilli have been observed at some localities: they are 10-20 cm thick, and are associated with abundant lithic fragments. These deposits can be referred to the 1631 AD eruption, which was the last large explosive event of Vesuvius (Di Vito et al. 1998). As remarked above, the pyroclastic deposits, and in particular the finer ash layers, are often reworked. When reworked, the grain size distribution ranges from slightly clayey, silty sand to gravels with silty sand. The deposits also include high amount of organic matter (well below the top-soil level) and sometimes fragments of carbonate rocks. Evidence of reworking are most clear at the base of the pyroclastic sequence, where, at the contact with the carbonates, brown plastic, organic matter-rich, clayey ash levels have been often observed.

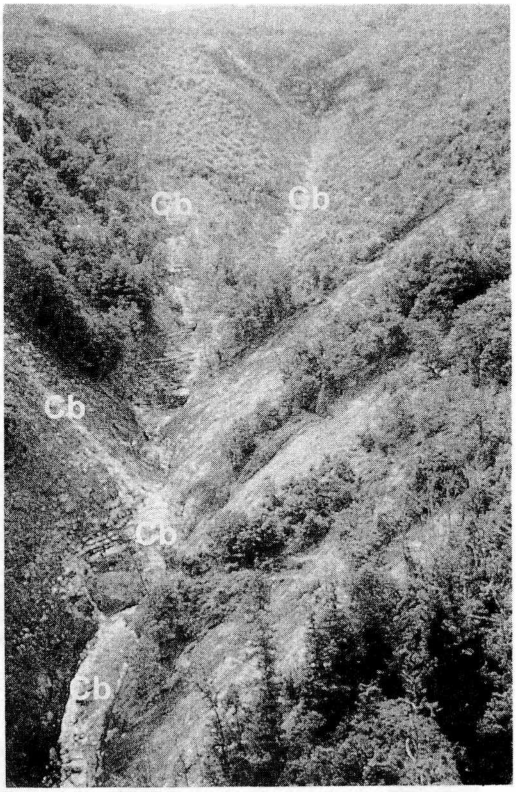

Figure 4. Bird-eye view of the landslides in the east branch (right in Fig. 2) of Vallone Connola. Note the erosion in the channel with exposure of the carbonate bedrock (Cb).

3 THE VALLONE CONNOLA - VALLONE S. FRANCESCO LANDSLIDES

In the Vallone Connola – Vallone S. Francesco area about 50 individual landslides have been surveyed and mapped (Fig. 2 and Table 1), of more than 300 slope movements documented in the Quindici area (Calcaterra et al. 1999a). The movements started as multiple (*sensu* WP/WLI 1993) soil slides (Fig. 4), which then converged in three main channelized flows, moving along the existing steep valleys. In this movement toward the lower slopes, the high velocities promoted deep erosion at the channel bottom and along the valley sides, thus adding new material and increasing the overall volume of landslide debris. Initial movements started from the uppermost portions of both channels in the Vallone Connola and along the main channel of the Vallone S. Francesco, at elevations above 900 m a.s.l. Addi-

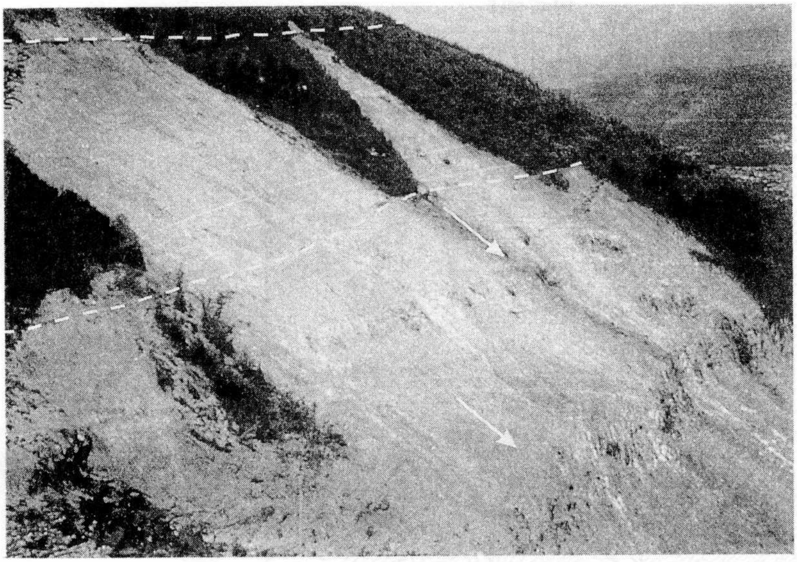

Figure 5. Zone of detachment and initial flow of triangle-shaped soil slides in the west branch (left in Fig. 2) of Vallone Connola. Dashed lines indicate the course of the pathways; arrows point to sub-vertical carbonate cliffs.

tional minor isolated slides occurred at yet higher elevations, and mostly in correspondence with the course of pathways illustrated in Figure 5.

Despite the development of numerous soil slides in both branches of the Vallone Connola, those which occurred in the right branch maintained their individuality and merged only after that the main channel was reached. The landslides in the left branch, however, were able to progressively increase their volume by enlargement along their flanks and the entrapping of additional material. This caused wide portions of the slope to be denuded, so that the distinctions between individual landslides are made more difficult. Downslope of the confluence between the two branches, the landslide debris moved as a channelized flow within the Vallone Connola. An approximately 8 m-deep channel contained the flowing debris, and only a minor part of this debris overflowed at the bend located at 360 m a.s.l.; all remaining debris, on the other hand, reached the higher-order channel (Lagno di Quindici) at the footslope (Fig. 2).

The landslides at Vallone S. Francesco mainly cluster around the valley axis, apart from two isolated soil slides at the west valleyside. The latter moved from breaks in the slopes due, respectively, to a limestone cliff and a bend in a pathway. Several additional small landslides are present in the Vallone S. Francesco, and are generally located at the limits of mountain roads or pathways.

An outline of the overall area involved in landsliding in the Vallone Connola – Vallone S. Francesco area is shown in Figure 2, while Figure 6 is a

Table 1. Main morphometric parameters in source areas of the 1998 landsliding events at Quindici (complete sample and Connola – S. Francesco area).

Parameter		Quindici territory *(308 events)*	Connola – S. Francesco *(53 events)*
Area (m^2)	*mean*	691.6	1395
	min	25	30
	max	9000	5625
	st.dev.	986.5	1338
Volume (m^3)	*mean*	1244	3072
	min	25	30
	max	16,875	16,875
	st.dev.	2003	3670
Length (m)	*mean*	30.3	51.5
	min	5	5
	max	135	135
	st.dev.	25.1	36.1
Max width (m)	*mean*	20.7	29.5
	min	2	3
	max	100	80
	st.dev.	15.7	16
Vertical relief (m)	*mean*	23.3	41.9
	min	2	2
	max	120	120
	st.dev.	21.4	30
Slope (°)	*mean*	36	37.6
	min	12	22
	max	56	49
	st.dev.	6.1	5.4

landslide zonation based on the processes which acted in different sectors of the landslides. Six zones were distinguished on the basis of air photo interpretation and detailed field surveys. The detachment area comprises the sector where surface of rupture

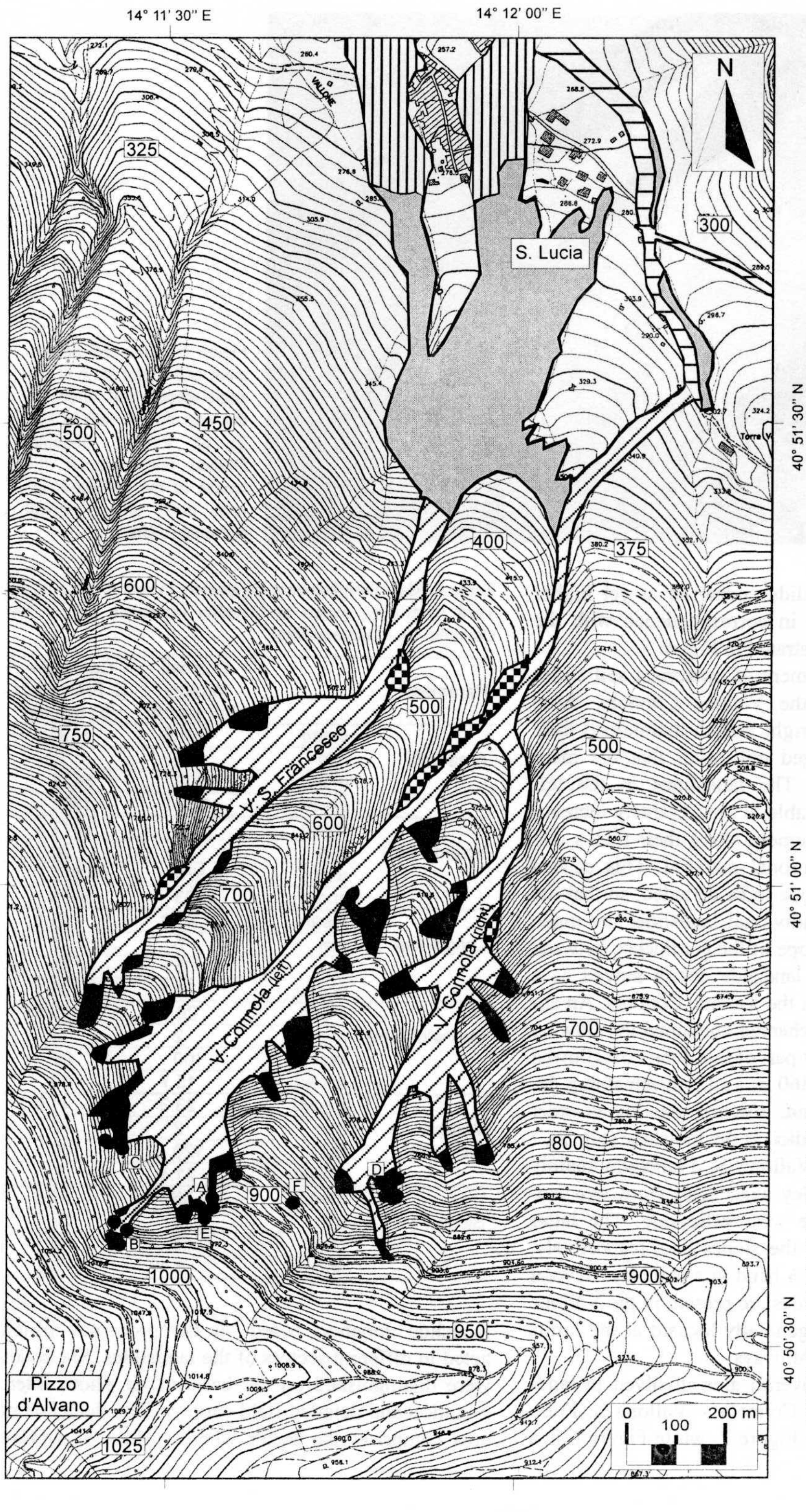

Figure 6. Zonation of the Connola - S. Francesco area. Legend: 1) Zone of detachment; 2) Zone of erosion - transport; 3) Zone of erosion - deposition; 4) Lateral landslide, showing retrogressive distribution of activity; 5) Zone of deposition; 6) Zone of canalization; 7) Location of the stratigraphic profiles (letters refer to Fig. 3).

(IAEG Commission on Landslides 1990) is exposed: as the lower limit of this area we considered any slope break, both natural (limestone cliff) or man-made (pathway), which forced the moving detached material to negotiate a jump and then to drop with renewed kinetic energy on the slope, triggering in this fashion the removal of yet additional material and/or the enlargement of the landslide limits. This general process caused the development of a triangular shape in the landslide detachment area, which was first observed in slope movements involving the pyroclastic deposits of Campania by Lazzari (1954).

Downslope from the detachment area, a zone formed by the combined action of erosion and downslope transport is present (Fig. 6): removal of the additional pyroclastic cover is again very shallow, as testified by the small preserved patches of vegetational cover; the surficial character is additionally shown by the trace of the original pathways, still recognizable in completely denuded areas. The spatial extension of the erosion/transport zone is noticeably wider than that of the detachment area, confirming the very high potential of erosion of the May 1998 landslides. Downslope movement of material within the main drainage channels caused also a lateral erosion of the valleysides for a height of a few metres, triggering additional landslides. The latter landslides showed a retrogressive distribution of activity with detachment of the material proceeding towards higher elevations (Fig. 4). In some cases, retrogression stopped when a vertical carbonate cliff was encountered. Since Vallone Connola is very narrow and deeply incised for its entire length, the erosion/transport zone extended down to the connection with the Lagno di Quindici (Fig. 6). On the other hand, Vallone S. Francesco widens gradually, and a well-defined fan is present at the mouth of the valley. From this sector, therefore, landslide debris was allowed to expand over a wider area. The widening of the flow caused a reduction in the velocity, and consequently the deposition began, marked by a shallow layer (a few centimetres to some decimetres in thickness) of landslide debris (see Fig. 7). Nevertheless, the flow velocity was still so high that the mobilized materials continued to erode surficial portion of the slopes, completely removing vegetational cover.

After the impact with the initial obstacles (i.e. buildings and other man-made structures), deposition of a great part of the debris took place in the historical area of Quindici (Via Casamanzi and Piazza Municipio), where the loss of 11 lives occurred, and the major damage was recorded. The most fluid portion of the landslide continued to flow (within the zone of canalization), following the network of roads and man-made channels (Fig. 6). Some of these channels date from 17^{th} to 19^{th} century and are locally known as "Regi Lagni".

To understand the contributions of debris-flow processes to the construction of the fan at the mouth of Vallone S. Francesco, a detailed sedimentological analysis has been performed, based on trenches excavated to a depth of about 5 m, and on observations of the available exposures of the fan surface. The main features of the S. Francesco fan deposits are:

1) marked lateral and vertical variations among massive, chaotic deposits and deposits with preserved fine-scale sedimentary structures (bedding, cross-lamination, etc.);
2) angular carbonate boulders (50 cm in max diameter), in a silty-sandy matrix; and
3) 10-20 cm-thick deposits laid down by the May 1998 event, and represented essentially by a pumice and a hazelnut-rich thin layer.

Based on the stratigraphy of the observed deposits, the S. Francesco fan is considered to be a mixed fan, fed both by water-laid and gravitational processes, the latter being essentially of the debris-flow type.

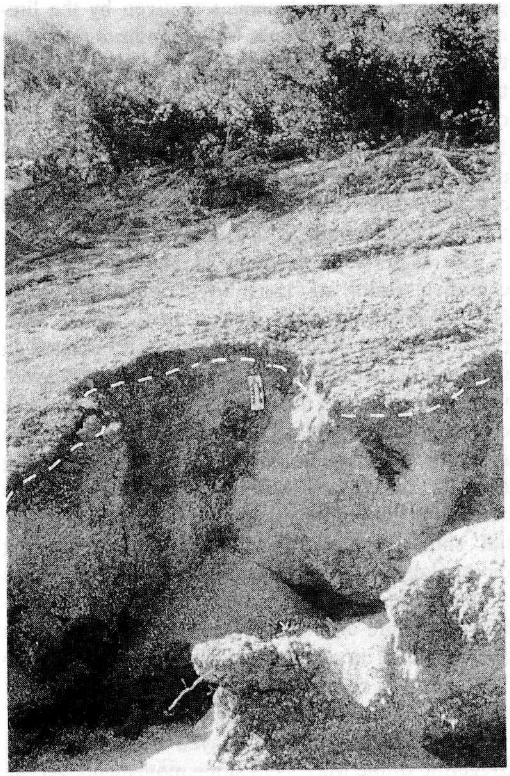

Figure 7. Zone of erosion-deposition at the mouth of Vallone S. Francesco. The dashed line separates the thin debris of the May 5, 1998, landslides from the underlying mixed deposits.

4 DISCUSSION

The May 5, 1998, event at Quindici confirmed the high landslide-prone vulnerability of the settlements located at the foothills of the steep carbonate mountains of Campania, as already verified in other settings of the region such as the Sorrento Peninsula. This peculiar condition is related to the presence of pyroclastic deposits derived from the impressive volcanic activity of both Mt. Somma-Vesuvius and the Phlegrean Fields. In the past 40,000 years, at least 10 major explosive (plinian or sub-plinian) eruptions have occurred, with a wide distribution of related volcaniclastic products (Di Vito et al. 1998). As a consequence, the primary instability-inducing factor is undoubtedly the pyroclastic cover itself, which mantles the underlying, complex karst-induced morphology of the carbonate bedrock. The observed small thickness of the volcaniclastic products is certainly due to gravity-related processes: within the Quindici area, the lowest thickness values were generally found to be in the high gradient slopes (from 30° to 60° and more) and, in particular, near the 1998 detachment zone. Further evidence of gravitational morphodynamics is given by the limited presence on the slopes of the products related to the 1631 AD huge Vesuvian eruption; these were, on the other hand, frequently recognized in the trenches on the S. Francesco fan. It is worth recalling that the 1632 and 1640 floods, which covered Quindici and neighbouring towns, were fed by the 1631 volcaniclastic products; the 1640 flooding event caused 40 victims (Calcaterra et al. 2000).

The high slope gradient is another important causative factor of instability. Calcaterra et al. (1999a) already pointed out that, of the whole sample of 308 individual landslides which occurred in the Quindici area in May 1998, the highest concentration took place in the range 31°-43°, with the peak corresponding to 39°. In the Connola - S. Francesco area, the detachment zones show values ranging from 22° to 49°, which coincide in the 80% of the cases with pre-failure values; this means that the initial sliding essentially followed the pre-existing morphology of the carbonate bedrock. Moreover, as is evident from Figure 3, most instances of the surface of rupture originated within a pumice layer, as already noted in similar landslides of the January 1997 event in the Sorrento Peninsula (Calcaterra et al. 1999b, Di Crescenzo & Santo 1999).

Rainfall also, of course, played a key role in the triggering of the May 1998 slope movements. At the time of the first landslides (12:00-12:30 PM – local summer-time) about 120 mm of rainfall had fallen, with a peak hourly intensity of 15 mm and an average value of about 5 mm/hr (Calcaterra et al. 2000). In Calcaterra et al. (2000), a historical and statistical analysis has shown that the antecedent rainfall for the 1998 event could be considered as "heavy" or "intense", but certainly not "extreme": in fact, the May 5, 1998, 1- to 48-hours antecedent rainfall has return periods lower than 5 years. Before 1998, the Quindici area suffered in the past from at least another 10 rainfall-induced landsliding events, the oldest documented of which is the flood of 1632 mentioned above. The sedimentological study of the S. Francesco fan provided further evidence of previous debris flow-like events.

Several factors contributed to the mechanism of the 1998 landslides at Quindici: among these, the presence of winding pathways deserves mention. The lack of drainage works and inadequate maintenance of the pathways favoured concentration of and erosion by the flowing water, and the development of many decimetre-deep gullies. Corresponding to bends in the pathways, water was free to move down slope, and therefore able to trigger many landslides. The presence of natural or artificial breaks in the continuity of slopes, besides favouring the trigger of soil slides, was also responsible for an additional effect, deriving from the jump of moving material when encountering steps related to pathways or cliffs: this provided further kinetic energy to the downward-moving debris, triggering the detachment of yet additional material and/or the enlargement of the landslide area downvalley. A similar jumping effect was also produced by the morphology of the S. Francesco fan, and has been clearly documented by amateur video-recordings: the high energy so acquired by the debris (moving at velocity estimated in about 15-20 m/s), produced a catastrophic invasion of inhabited areas, where the debris reached heights of up to 5 m. The high energy of the flow is further illustrated by its ability to move and transport carbonate blocks up to 7-8 tons in weight, within the Quindici area.

5 CONCLUSION

The May 5, 1998, events in the Campania region brought about a greater public awareness of the threat posed by fast-moving, rainfall-induced slope movements. Immediately after that event, two daily rainfall thresholds (40 and 60 mm, respectively) have been defined by the Civil Protection Department for alert and alarm actions in areas affected by landslides. The occurrence of debris-flow phenomena in distinctly different settings in the region (Sorrento Peninsula, Naples, Phlegrean Fields, the island of Ischia) compelled the scientific community to carry out research concerning geologic and geomorphological aspects of the area's slope movements. The results so far obtained show that, despite some basic difference in the physical contexts, debris flows affecting the Campanian volcaniclastic deposits generally represent the evolution of first-time, small-size, shallow soil slides. The surface of rupture of the latter often coincides with a pumice layer, which mimics the overall morphology of the local bedrock. The turning point in the evolution from slide to flow is often provided by a break in slope, causing, in turn, a "jump and fall" effect, responsible for the triggering of the flow in underlying, water-saturated pyroclastics.

On the other hand, the role played by additional factors is not completely agreed upon: as in the case, for instance, of subsurface ground-water circulation. It is now debated whether or not excess pore pressures linked to heavy or extreme rainfall events occurs within the pyroclastic sequence (for example, in a more permeable pumice layer bounded by finer ash levels) or within the underlying carbonate sequence. At Quindici, elements supporting both hypotheses have been observed (i.e. piping in the pyroclastics and water flowing from the karst cavities). These considerations are among the crucial factors that must be considered in future research aimed at an understanding of the mechanisms controlling the development of slope failures at Quindici and the nearby areas. The May 5, 1998, event represented, therefore, an opportunity for scientists to understand such phenomena, in an environment of increased public interest and concern. Good results have already been achieved from a multi-disciplinary perspective; however, much needs to be done in order to mitigate the debris-flow risk in the numerous settlements located at the foothills of the carbonate mountains in Campania.

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