Preliminary report on the landslides of 5 May 1998, Campania, southern Italy

M. Del Prete, F. M. Guadagno, A. B. Hawkins

Abstract Following intense rainfall on 4/5 May 1998, over 100 mass movements occurred in the Sarno-Quindici area, some 30 km east of Naples, southern Italy. The movements took place in an area where recent pyroclastic materials mantle a Mesozoic limestone bedrock massif which had already suffered karstification over a long period. The debris from these movements extended 3–4 km into the surrounding lowlands and reached the towns of Sarno, Quindici, Bracigliano and Siano, causing severe destruction. One hundred and sixty-one people lost their lives. This preliminary paper discusses a number of scenarios to highlight the possible causes and mechanisms of the movements. Of particular importance are preceding rainfall patterns, the possible perched water conditions, the physical properties of the recent metastable volcanoclastics and underlying palaeosols and the influence of man-made changes in the morphology. Further studies are being undertaken to elucidate the relative importance of the different contributory factors.

Résumé Suite aux intenses précipitations du 4/5 mai 1998, plus d'une containe de mouvements de terrain se sont produits dans la région de Sarno-Quindici, à environ 30 km à l'est de Naples, dans le sud de l'Italic. Les mouvements de terrain sont situés dans une zone où des matériaux pyroclastiques recents recouvrent un substratum calcaire du Mésozoïque ayant déjà subi une karstification pendant une longue période. Les coulées de débris issues de ces mouvements de terrain se sont propagés sur 3 à 4 km à l'intérieur des plaines environnantes et ont atteint les villes de Sarno, Quindici, Bracigliano et Siano, en causant de graves destructions. 160 personnes ont péri. Cet article préliminaire examine plusieurs scénarios afin de mettre en lumière les causes et mécanismes possibles des mouvements de terrain. Sont particulièrement importants les scénarios des précipitations antérieures, l'éventualité de nappe d'eau perchée, les propriétés physiques des roches volcaniques métastables récentes et des paléosols sous jacents et l'influence des changements morphologiques d'origine anthropique. Des études plus poussées sont entreprises pour déterminer l'importance relative de ces différents facteurs.

Key words Landslides · Debris flows · Perched water · Undrained loading · Fluidisation · Italy

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Introduction

In the western Campanian Apennines of southern Italy much of the bedrock is formed of limestone (Ippolito et al. 1975) on and in which natural karstic geomorphological processes have taken place (Brancaccio 1968). During periods of volcanic activity, this karstic landscape was mantled with varying thicknesses of pyroclastic materials. The last major event was the 79 A.D. eruption of Mount Vesuvius, well known for its consequences for Pompeii (Lirer et al. 1973; Sigurdisson et al. 1985; Santacroce 1987). Inland of Mount Vesuvius, towns and villages grew up on the fertile volcanic ash deposits surrounding the hills. In the last 50 years, extensive urbanisation has taken place in these areas, which often act as commuter towns for Naples.

Mass movements are common in the pyroclastic mantle, evidenced by the pronounced scars on the hillsides (Guadagno 1991). The accumulation of disturbed material is thickest in the concave zone along the lower part of the foothills. Periodically the debris from the mass movements

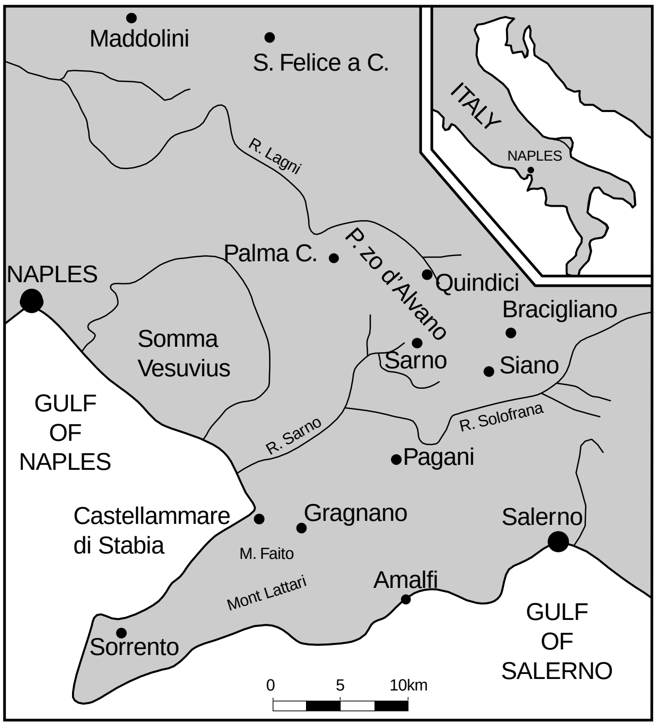


Fig. 1
Location map showing towns affected by the May 1998 events

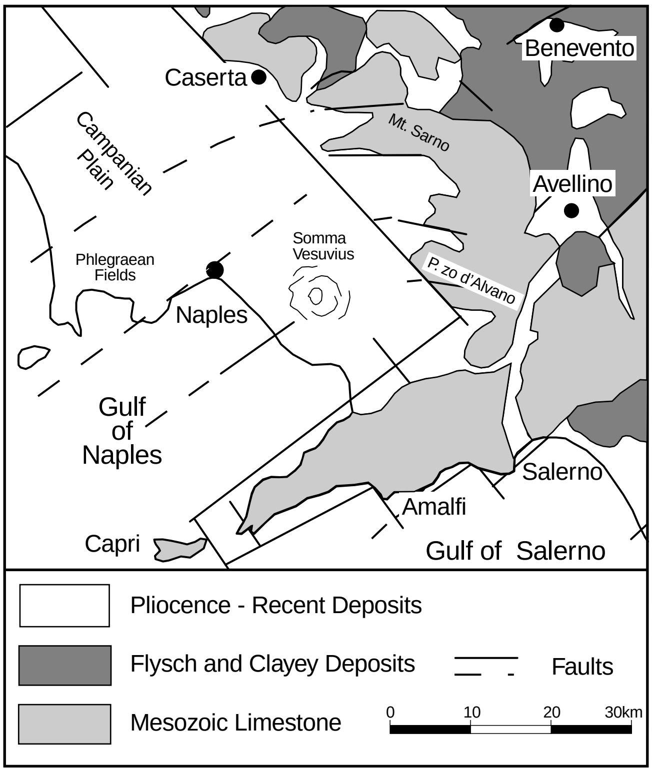


Fig. 2
Simplified geological map showing the locations of some of the major faults

extends into the settlements while water released at the time of the events passes as torrential flows across the adjacent lowland areas.

On 5 May 1998, at a time of heavy rainfall, over a hundred individual mass movements took place, mainly around the limestone ridge of P.zo d'Alvano. On the night of 5 May the towns of Sarno, Quindici, Bracigliano and Siano, some 30 km east of Naples (Fig. 1), were badly affected with significant destruction. One hundred and sixty-one people lost their lives. The disaster was in part due to the passage of fluidised mud and in part to water with a high proportion of suspended material (Celico and Guadagno 1998).

This paper records the major events which are known to have occurred in the area around Vesuvius since 1841 and the rainfall data relevant to the May 1998 event. The geological/geomorphological setting and the nature of the recent mass movements is described and some possible causes and mechanisms discussed.

Geological setting

The geology of the area in which the landslips took place consists dominantly of limestones of Cretaceous age, belonging to carbonate platform sediments formed between the Triassic and the Palaeocene periods (Fig. 2). The bedding thickness generally varies from a half to several metres, although at some levels it is only a few millimetres thick. The sediments dip up to 30° from the horizontal. Joints are typical of those anticipated in a strong, brittle limestone, the master joints generally trending NE-SW and NW-SE, similar to the main fault features. The marine sediments were uplifted as part of the Miocene/Alpine orogenic episode when extensive thrust movement took place followed by wrench faulting.

During the Pliocene and extending into the Pleistocene, tensional movements induced the formation of normal faulting to create an horst-graben relief (Ippolito et al. 1975). One of the grabens is now occupied to a large extent by the Gulf of Naples. Marine and pyroclastic deposits accumulated within the graben, through which the main volcanicity of the Phlegraean Fields and Somma erupted. These deposits now form the general coastal lowlands to the north of Naples. Radio-carbon dating indicates that volcanic activity associated with Somma took place at least 22,000 years B.P. From field evidence it is likely that earlier deposits also are present but it is not possible to be confident of their age (Santacroce 1987).

The karst morphology of the limestone massifs includes a number of stream/dry valley features. These extend from near the crest of the hills and are probably related to the joint system and faulting within the bedrock. The nature of these valleys suggests that they were eroded during the "Ice Age", at a time when the ground waters were temporarily frozen such that surface erosion took place. Some of the faults and joints within the limestones have been enlarged by dissolution while underground drainage systems would undoubtedly have resulted in conduit flow and the forma-

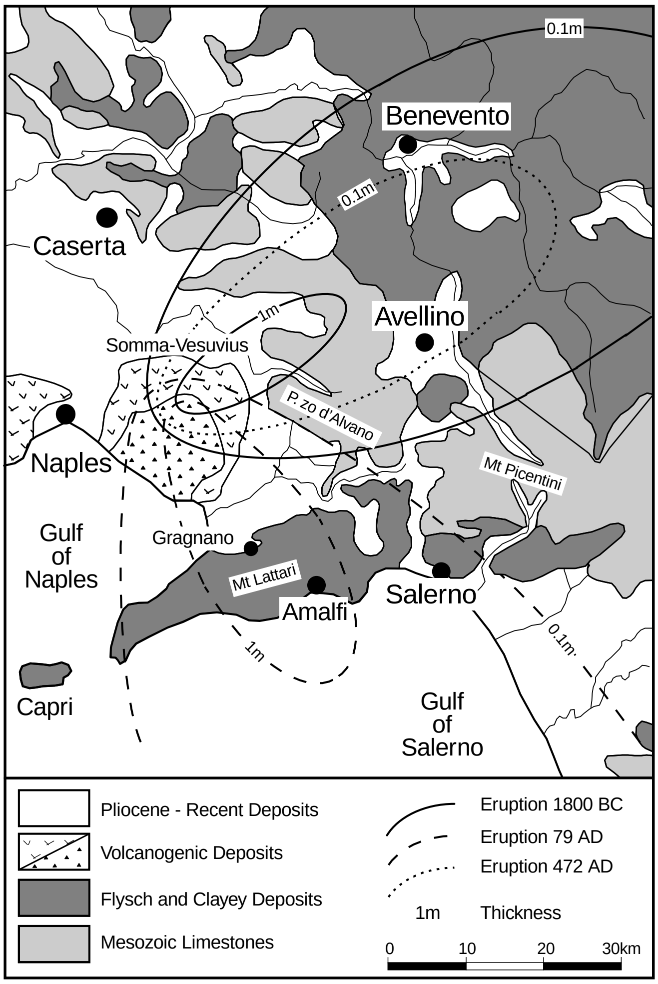


Fig. 3
Zones over which the airfall deposits from three eruptions of Somma Vesuvius accumulated

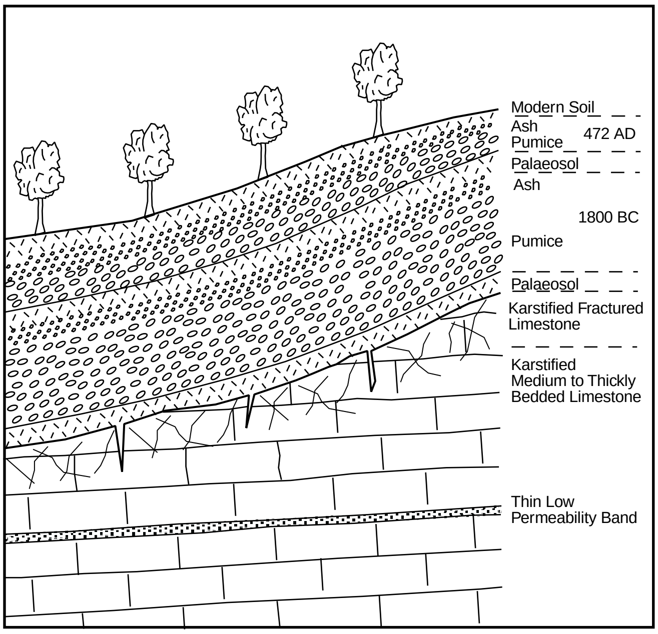


Fig. 4
Schematic profile of the pyroclastic deposits in the area of the P.zo d'Alvano

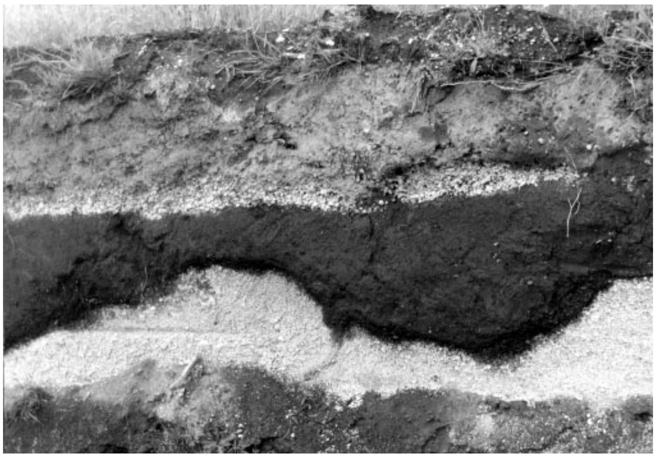


Fig. 5
Typical pyroclastic deposit showing variation in individual layer thicknesses

tion of springs around the hills at the elevations where lower permeability bands outcrop. Few perennial springs exist today, the most important egressing at Sarno. It is of note that on the top of P.zo d'Alvano, between the highest point (1133 m) and Mt. Torrenone (1071 m) there is a large hollow in which the elevation drops to below 850 m. This has the appearance of a doline and is believed to have been caused by karstic processes.

Above the very thin soil which formed on the limestone bedrock, the pyroclastic deposits of the Somma-Vesuvius eruptions now mantle many of the hill slopes. These airfall deposits accumulated following the eruptions of 1,800 B.C., 79 A.D. and 472 A.D.; the areas in which they were deposited being largely controlled by the prevailing wind direction. Figure 3 gives the general thickness of the volcanoclastic material, indicating that as a result of the 79 A.D. eruption Gragnano, to the south of Vesuvius, received 1 m of cover and that P.zo d'Alvano to the east of Vesuvius had nearly 1 m of cover as a result of the 1,800 B.C. eruption followed by a further covering of some 0.1 m in the 472 A.D. event. Above the lower pumice/ash deposit a second palaeosol is frequently present while a thin surface soil is developing on the upper pyroclastic layer (Fig. 4).

As would be expected, therefore, the pyroclastic mantle varies in thickness (Fig. 5). This was controlled in part by geographical location, in part by the relief on which the deposits accumulated and also by the surface morphology of the wind-blown deposits as they stabilised and the process of soil formation began. At the top of P.zo d'Alvano, for instance, the cover is thin yet on the lower parts of the hill slope it is sometimes several metres thick (Celico et al. 1986). Not surprisingly, where thick limestone bands and associated topographical steps are present, the deposits are

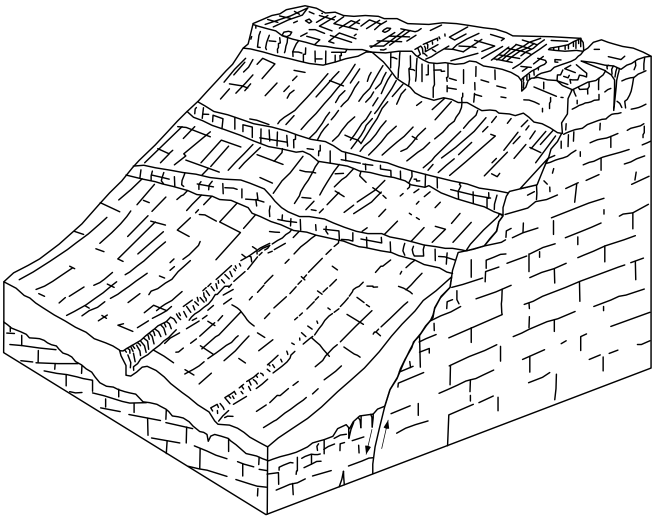


Fig. 6
Sketch indicating the varying thicknesses of pyroclastic deposits over stepped limestone relief

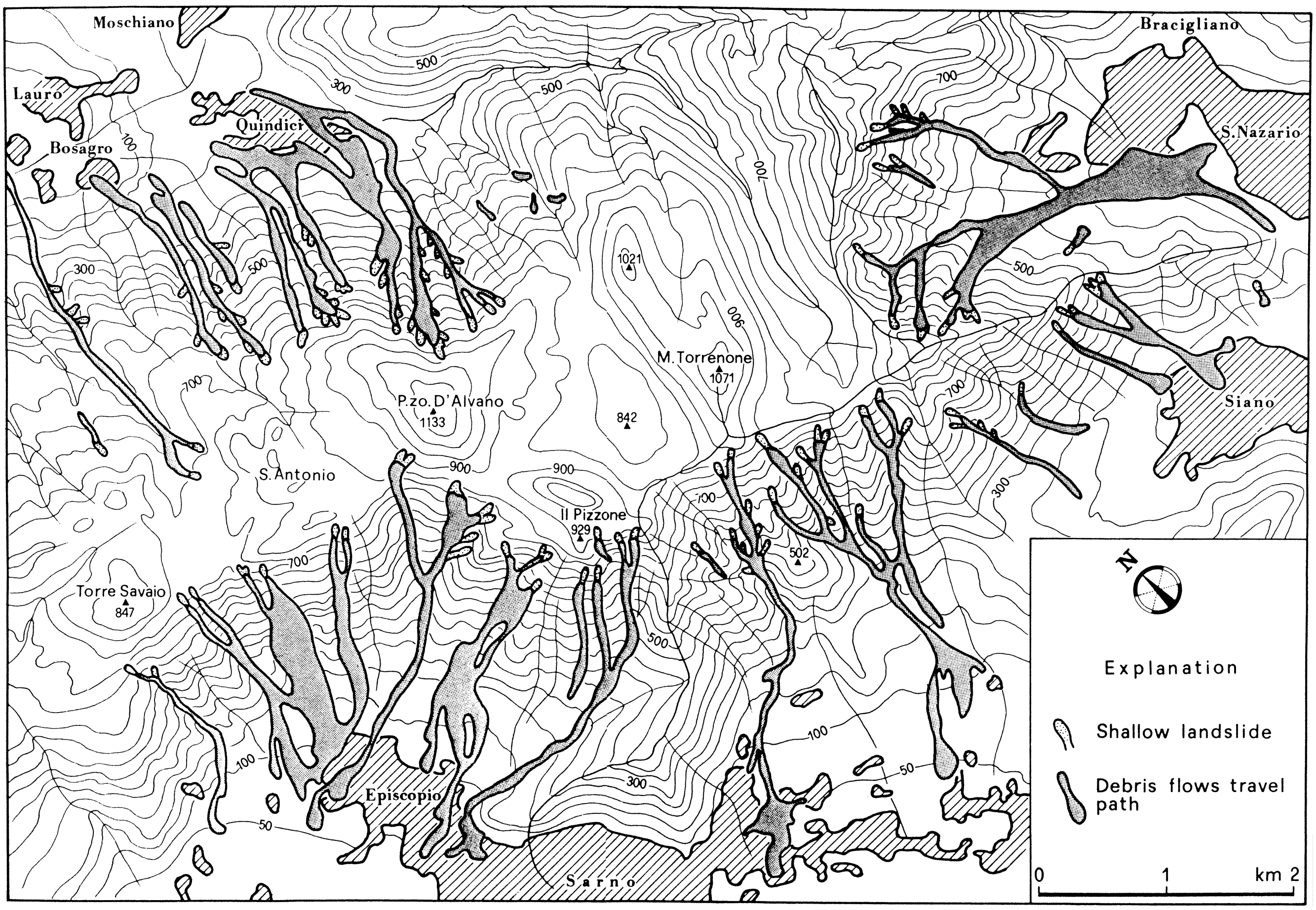
thicker in the hollows than on the sub-vertical faces, as seen in outcrops on the northern slopes of P.zo d'Alvano (Fig. 6). Whilst layering is evident in the undisturbed material (Fig. 4) the lack of clear layering in some of the lower slope deposits implies that the material was probably redeposited as a result of colluvial and gravitational processes.

Geomorphology

The geomorphological setting is strongly influenced by the past tectonic activity which has dissected the limestone terrain of Campania into a series of massifs (Brancaccio et al. 1978). The P.zo d'Alvano, on which more than 100 landslides took place on 5 May 1998, is a southeast-northwest structure from which a number of gullies extend in an almost radial pattern, incised into the hill slope by up to 30 m. The spatial distribution of these gullies can be seen in Fig. 7 which highlights those in which the recent instabilities took place.

As a consequence of its airfall origin, the pyroclastic cover would originally have effectively obliterated any surface irregularities existing in the karst morphology, creating an almost smooth topography; although notably along the northern slopes some pronounced steps are visible where

Fig. 7
Spatial distribution of the gullies around P.zo d'Alvano highlighting those in which mass movement took place in May 1998



thick limestone horizons form vertical faces. These limestones are most pronounced in the upper part of the hill and less obvious within the gullies. Between the limestone outcrops the slopes are generally in the order of 40°–50° and vegetated with grass and/or trees. Such steep slope angles are difficult to explain, although they would have originally been related to the maximum angle of repose of the airfall material. Possible explanations include:

1. The low density of the material, as a consequence of the voided nature of the pumice and the lack of packing of the finer ash deposits.
2. The roughness of the pumice particles and the unloaded packing of the ash, such that the grain mass behaves as a series of angular fragments.
3. Soil suction related in part to the more permeable limestone bedrock which is known to have a karstic surface. The karstic nature would cause underdrainage of the mantle deposits.
4. The presence of vegetation around and into which the pyroclastic deposits fell.

Although there are few records of the ancient vegetative cover to the area, it is understood that the Romans took advantage of the more moist atmosphere of the d'Alvano mountains to develop horse chestnut plantations. More recently the area has been extensively forested with hazel nuts. Both species can survive with shallow roots – an important feature on the high slopes where only a thin veneer of soil exists. It has been noted that while some roots have extended into ashy soils present within hollows in the limestones, they do not penetrate further into the underlying dry limestone bedrock.

Initially access to the plantations was by foot hence only limited pathways were created. More recently however, larger trackways have been developed for vehicular access. As the roadways were cut into the upslope side of the hill and material deposited on the downslope side, the pushed material exacerbated the potential instability of the already steep slopes (see Fig. 8). Whilst some of these trackways rise in a zig-zag manner up the slope, many have been cut almost parallel to the contour.

Fig. 8
Typical trackway cut into the hill slope. Note extensive accumulation of material immediately downslope

Rainfall

This part of southern Italy has a typical Mediterranean upland climate with hot dry summers and warm wet winters. Whilst even in winter there may be many days without a measurable rainfall, 30–60 mm of precipitation in a single day is not atypical. A histogram showing the monthly rainfall for Sarno between 1981 and 1990 is given in Fig. 9.

The nearest weather station to the d'Alvano massif is at Ponte Camerelle, some 97 m above sea level and 10 km southeast of Quindici, the town in which most destruction took place as a consequence of the recent mass movements. It is well known locally that significantly more rain falls on the hill mass than in the surrounding lowland towns, hence the rainfall data obtained from the Ponte Camerelle weather station does not necessarily reflect the intensity of the precipitation on the hill mass and/or the relative humidity in this area. Elsewhere in southern Italy (Celico 1983) it has been shown that there is approximately one third more annual rainfall in the upland areas than in

Fig. 9
Histogram showing the monthly rainfall recorded at the Ponte Camerelle weather station 1981–1990

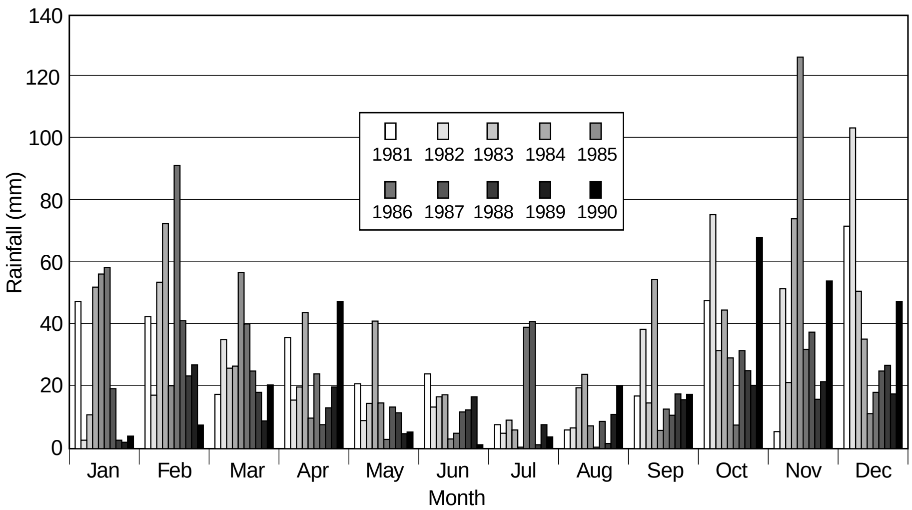


Table 1
Rainfall records from Ponte Camerelle (Nocera Superiore), January to May 1998

Day	January	February	March	April	May
1	0	14.2	0	0	3.8
2	1.4	0	0	0	2.6
3	5	1.4	0	0.4	0
4	0	45.6	0	0	37.6
5	0.4	2.8	0	0	58
6	0	0	0	0	0.3
7	0	0	0	0	
8	0	0	0	0	
9	0	0	17	1.4	
10	0.2	0	0	0	
11	0	0	0	3.3	
12	0	0	0.6	3.2	
13	0	0	34.4	17.3	
14	0	0	0	10	
15	2.2	0	0	0	
16	2.6	0	0	18	
17	9.8	0	0	34	
18	0	0	0	26.4	
19	24	0	6.8	9.8	
20	6.4	0	0	4.8	
21	1	0	1.6	0	
22	0	0	0	0	
23	0	8	0	0.6	
24	0	8	19.4	0	
25	0	5.2	23	0	
26	0	0	0	0	
27	0	0	0	0	
28	0		0	36.6	
29	0		0	7	
30	0		0	1.4	
31	16.6		0		
Total	69.6	85.2	102.8	175.2	

the lowlands. In this area, however, it is not known whether this additional 30–40% rainfall relates to a greater number of days on which rain fell or more intense precipitation over the same number of days.

The 1998 records from Ponte Camerelle (Table 1) indicate that rain fell on 10 days in January 1998 giving a total of 70 mm. In February the total of 85 mm fell on 7 days, of which 45.6 mm was recorded on 4 February. In March rain fell on 7 days, giving a total of 103 mm, while in April the total of 175 mm rain fell on 15 days, with 88 mm recorded between 16 and 19 April. In May a total of 102 mm fell between the 1st and 5th with only 1 dry day, 3 May. Of this, 95.6 mm fell in the 2-day period of 4/5 May. It is of note that between 28 April and 5 May there was only one dry day (3 May) and that a total of 147 mm rain fell in this 8-day period.

In view of the high precipitation immediately preceding the large scale mass movements of 5 May, it is likely the two events are related. What is not clear is the significance of the total accumulated rainfall and the extent to which the heavy rainfalls of mid-April affected the ground water regime in the bedrock and overlying cover material such that this second period of heavy precipitation in late April/early May could not be accommodated without slope failure.

Slope failures

Historic

Table 2 summarises the past instabilities recorded in the literature (Montella 1841; Ranieri 1841; Bordiga 1924; Cancellara 1954; Lazzari 1954; Penta et al. 1954; Civita et al. 1975; Guadagno et al. 1988; Guadagno 1991; Calcaterra et al. 1997) showing the dates on which they occurred and whether one or more than one failure took place (Celico and Guadagno 1998). Where possible the rainfall data are also included. The numbers in brackets indicate the number of consecutive days on which rainfall occurred to produce the cumulative figure provided in the table. Attention is drawn to the fact that the rainfall values were not obtained on the hill slopes or mountain top and hence may be an under-estimate of the precipitation actually falling on the hills.

In view of the spatial distribution of the pyroclastic mantle resulting from eruptions of Somma Vesuvius (Fig. 3) it is not surprising that the significant historic landslides recorded affected the Gragnano zone, the east and west coast of Sorrento Peninsula, Sarno-Palma-Campania and the inland areas between Salerno and Avellino.

The Gragnano area, approximately 15 km south of Vesuvius, is reported to have received a cover of over 1 m from the 79 A.D. eruption. On 22 January 1841, after a period of exceptional rain during which some 125 mm fell at the Naples station over a 4-day period, four large landslides occurred on the northern slope of Mount Pendolo, at the toe of which the village of Gragnano is situated. An architect at the time (Montella 1841) describes one of these mass movements as having a triangular shape; the apex reaching the middle of the slope of Mount Pendolo. Material disturbed by this mass movement reached the village of Gragnano and caused significant destruction, as recorded by Raineri (Fig. 10). Gragnano was also affected by an event in August 1935 when again mud invaded part of the village and by a major occurrence on 17 February 1963 when 14 landslides were triggered by the 249 mm rain which fell in a period of 3 days. On this occasion the urban areas of Castello, Aurano, Caprile and S. Nicola were also affected. The newspaper "Corriere di Napoli" describes tongues of mud penetrating deeply into Gragnano village.

Instabilities of the pyroclastic cover have also affected geomorphologically similar areas, such as at Amalfi and Salerno. Bordiga (1924) describes slips of the volcanoclastic cover which occurred on 24 October 1924, exposing the limestone bedrock. It is recorded that this event was probably triggered by 150 mm rain falling in an 18-h period. In the same area on 26 March 1924, after 102 mm rainfall in a single day, Passerini (1925) described chaotic masses moving downslope and reaching inhabited areas. He considered the main cause was fluidisation as a consequence of excessive pore water. Other similar events in October 1954

Table 2
Past instabilities recorded in the literature showing the dates on which they occurred and whether one or more than one failure took place. Numbers in parentheses are the number of consecutive days on which rain fell

Site	Date	Events	Rainfall (mm)	
Gragnano	22.01.1841	Multiple	122.6	(4)
Vettica–Conca–Praiano–Positano	26.03.1924	Multiple	102.4	(1)
Gragnano	28.05.1930	Single	Not available	
Gragnano–Castellammare	21.08.1935	Single	Not available	
Nocera–Sarno–Vietri	02.10.1949	Multiple	198	(1)
Pozzano	25.12.1950	Single	Not available	
Pozzano–Bagni	09.03.1951	Single	Not available	
Salerno–Minori–Tramonti–Cava–Vietri–Nocera	25.10.1954	Multiple	504	(1)
Nocera Inferiore	10.03.1958	Single	Not available	
San Felice a Cancello	15.10.1960	Single	Not available	
Nocera (S. Pantaleone)	08.12.1960	Single	148.8	(2)
Pama Campania	24.05.1962	Single	Not available	
Gragnano–Pimonte	17.02.1963	Multiple	249.2	(3)
Castellammare	17.02.1963	Single	249.2	(3)
Sarno	21.02.1963	Single	219	(7)
Salerno–Amalfi–Cava de'Tirreni	07.10.1963	Multiple	182.2	(5)
Vico Equense (Scrajo); Arola–Ticciano	23.11.1966	Single	198.9	(4)
Pozzano	14.04.1967	Single	Not available	
Sarno	09.01.1968	Single	Not available	
Cava de'Tirreni–Agerola–Scraio-Seiano	15.03.1969	Multiple	Not available	
Nocera (S. Pantaleone)	14.08.1970	Single	Not available	
Gragnano	02.01.1971	Single	159.6	(3)
Gragnano	21.01.1971	Single	196	(1)
Nocera (S. Pantaleone)	06.03.1972	Single	115	(2)
Mitigliano (S. Costanzo)	16.02.1973	Single	57	(3)
Vico Equense (Scrajo)	04.11.1980	Single	Not available	
Pozzano	14.11.1982	Single	Not available	
Palma Campania–Catellammare Vico Equenze	22.02.1986	Multiple	93	(5)
Gragnano-ss 145 km all'innesto ss 366	23.02.1987	Single	Not available	
Tramonti	07.01.1988	Single	Not available	
Pozzano	23.11.1991	Single	Not available	
Bracigliano	03.10.1992	Single	Not available	
Sarno	26.05.1994	Single	Not available	
Pozzano	10.01.1997	Multiple	56	(3)
Sarno–Quindici–San Felice a Cancello	05.05.1998	Multiple	92.4	(2)

Fig. 10
Impression of the town of Gragnano at the time of the 1841 mass movement, illustrated by Ranieri

are described by Lazzari (1954) and Penta et al. (1954). These affected the Salerno-Minori-Tramonti-Cava-Vietri-Nocera areas. On this occasion 504 mm rain are reported to have fallen on a single day.

In the Sorrento Peninsula, landslides occurred following 249 mm rainfall over 3 consecutive days in February 1963 and in November 1966 after 199 mm fell within 4 days. Other events took place in March 1969, November 1980, November 1982 and February 1986, the latter after some 93 mm rain fell over a period of 5 consecutive days. However, other landslides include those in November 1991 and January 1997 when the rainfall measurements at the lowland weather stations recorded as little as 56 mm precipitation. Civita and Lucini (1968), de Riso and Nota d'Elogio (1973) and Civita et al. (1975) describe such mass movements as sliding of the 1–3 m thick weathered pyroclastics on the calcareous bedrock. Calcaterra et al. (1997) conclude that the events of January 1997 were connected with cuts into the slope profile for the creation of vehicular accesses.

In the inland area of Sarno-Palma-Campania a large number of events have taken place with many recorded since February 1963. Among those best described are the events of 22 February 1986 which followed some 93 mm rain over 5 consecutive days. The details of the stratigraphy of the pyroclastic deposits overlying the limestone bedrock have been documented by Guadagno et al. (1988) and Vallario (1992). Vallario observed the area for 5 years following the major disturbance of February 1986 and records extensive infilling of the gullies. Undoubtedly part of the infill will have resulted from material being removed from the unprotected scars by rain or wind and transported downslope. Vallario did not take accurate measurements but from his field observations estimated a relatively rapid increase of accumulation in the gullies. Such infill following one event may well contribute to subsequent failures.

Fig. 12
Mud splattered on walls of S. Pietro church, adjacent to the Bourbon culvert, Quindici

Events of 5 May 1998

Effects in populated areas

The areas in which slope failures took place on 5 May 1998 are shown in Fig. 7 (Celico and Guadagno 1998). Of most significance for the local population were those which occurred upslope of the towns of Quindici and Sarno. The latter was originally built in an area where springs egress, although the town itself was constructed along an almost straight area of the hill slope which contained no obvious gullies. Whether the earlier inhabitants had appreciated the significance of the hill slope topography is not known but in the last 50 years the town has extended to the east and west. As seen in Fig. 7, the 1998 debris fan penetrated into these more recent suburbs. A number of structures were destroyed and a significant area left with a thin veneer of re-deposited ash and pumice (Fig. 11).
Quindici, however, was built partly on an interfluve between two pronounced gullies. The importance of river flow in this area was appreciated as long ago as the Bourbon dynasty when lined culverts some 8 m wide and 2 m deep were constructed. The first warnings of impending disaster in Quindici were the increased height of water in the culvert and some rumbles from the mountain slopes. As a result, the Mayor declared that the town should be evacuated in view of the possibility of a flood. Unfortunately some of the inhabitants who did not heed this warning and remained in the town lost their lives.

Fig. 11
Indication of the extent of the debris which penetrated into the town of Sarno

Mass movement in both gullies affected Quindici. On reaching the valley floor, the main eastern debris flow turned westwards following the line of the Bourbon culvert to the north of the town. At the change of direction the debris indicates that the mass flow was some 3–3.5 m high. As the material passed down the culvert, the flow was impeded by low bridges and consequently spilt into the surrounding area. Tree trunks carried in the debris could not pass easily beneath the bridges and turbulence developed. Evidence of the turbulence and splashing is clearly visible on structures, including the south end of the S. Pietro church (Fig. 12).
Material from the western gully, however, passed directly through the town of Quindici. As it flowed downslope across a nut plantation and farming development, its direction was impeded by the presence of houses constructed on the northern side of a street. Following the line of least resistance, it passed down the road through the town. As can be seen from Fig. 13, when deflected by houses the height of the mud rose to cover the roof of a house and in some places reached over 5 m above road level. At least 10–20 houses were destroyed or rendered uninhabitable. Figure 14 shows two houses effectively demolished, two temporary support archways and the height reached by the deposits at the point of constriction.
In view of the immediate response of the Italian firemen, police and army and other volunteers in removing the accumulated debris, it is difficult to quantify the volume of material involved but the extent to which it penetrated into Quindici can be seen from Fig. 15. Upslope of the town, a width of some 100 m has been left veneered by a 100–500 mm thick debris blanket. Whilst this consisted mainly of re-deposited ash and pumice, some large lime-

Fig. 13
Remains of the building which partly deflected the mass movement; note mud on the roof

Fig. 14
Indication of the damage in Quindici and the line showing the level to which the wave of debris reached

Fig. 15
Indication of the extent of the debris which penetrated into the town of Quindici

Fig. 16
View upslope over the debris from the mass movement showing the occasional limestone boulders

stone boulders up to $0.7 \times 1 \times 2$ m were also present (Fig. 16). Towards the edges of the flow the trees appear to have been pushed aside while the abundant fragments within the main mass indicate they were broken by the activity of the slide itself and by impact with encountered objects.

Whilst the main accumulation fans were relatively close to the base of the hill, some mud had been carried within streams for up to 7 km from the base of the slope as a hyperconcentrated flow (see Pearson and Costa 1987). Such debris was noted immediately after the 5 May event, particularly to the west of the d'Alvano massif.

Hill slope failures

Two main types of mass movements occurred: failures on areas of hill slope which appear almost straight and failures associated with gullies and their immediate side slopes (Celico and Guadagno 1998).

As seen in Fig. 17 the top of the gully failure zones is frequently near the crest of the hill. Although in some cases

Fig. 17
Typical view of the limestone massifs showing the gully failures extending almost to the crest of the hills

these are just above a vertical face of limestone, in other areas no limestone scars are present. Examination of the slope indicates that the failed material is almost exclusively volcanoclastic although the presence of boulders of limestone in the accumulation area indicates that some blocks of bedrock may have been dislodged. To date however, no evidence of where blocks may have recently been removed has been seen.

Possible causes

From the field observations and rainfall data a number of possible causes can be postulated. These are discussed below, in no preferential order.

1. The presence of lower permeability bands within the limestone sequence would hinder the downwards percolation of the water. Although in general the hill mass would have a low ground water regime, variations in perched water conditions would result in lateral flow and egress at approximately the level of these lower permeability horizons. Evidence of dissolution along bedding and joints has been observed in the field and at P.zo d'Alvano, for example, the re-cemented fault breccia seen in a roadside exposure could undoubtedly have caused a temporary "dam" within the limestone terrain, resulting in a localised increased water level. Where the failures have very open (straight) backscars, their origin may be related at least in part to sedimentological/ discontinuity features within the underlying limestone massif which, with heavy precipitation, could lead to a rise in perched water conditions. Such a temporary increase in water levels would result in the sudden development of egress points, hence a relatively quick increase in flow into the slope mantle. Although the increase in water level within the bedrock may be only some 0.5 m, in view of the conduit flows within the limestones, notably above lower permeability bands, the back pressures produced could be sufficient to effectively fluidise the overlying veneer, such that its intrinsic strength would be reduced and failure take place.
2. In some areas relatively straight failures also occur where trackways have recently been cut into the hill slope (see Fig. 8). Although these have been excavated mainly in the pyroclastic veneer, in some areas the trackways have involved limited excavation within the bedrock. These trackways would undoubtedly interrupt the normal downslope flow of surface water which would then be diverted along these partially unvegetated linear features. Where the volume of such flows was relatively high and weak zones were present on the downslope side, initial spillage of water could lead to failure of the downslope side of the trackway, through which the water would be diverted to create new channels within the uncemented pyroclastic veneer. This could account for the reported sudden rise in water in the Quindici culvert, followed by debris material as the mass movement developed at the head of the failure zone.
3. Once upslope failure has occurred, the sudden loading of saturated material downslope could result in rapid failure, similar to the flow slides described by Hutchinson (1986). Sudden mass falls onto the downslope material would be likely to produce the rumbling noted by the townspeople. The pyroclastic material existing in a metastable state would suddenly experience a marked increase in weight such that the soil structure would change while the pore water content remained constant. With the reduced pore space in the re-aligned soil, excess pore pressure for the new soil volume would be created and mass failure would take place.
4. Chemical analysis and SEM evidence indicate the presence of allophane within the ashy palaeosols overlying the limestones. This clay mineral is known for its capacity to expand and contract. In its expanded state the soil would have a high void ratio and consequently a high moisture content and low shear strength. Whilst normally the underlying soil horizon would be strong enough to support the steep pyroclastic mantle, during periods of intense rainfall, particularly if the material had already been saturated by the accumulated previous rainfall, the state of limiting equilibrium would be exceeded and the overlying pyroclastic and soil mass would fail by sliding. The effect of such slides in initiating debris flows is discussed by Fleming et al. (1989).
5. In view of the observed layering of soil, pumice and ash indicative of periodic eruptions interspersed with quiescent times in which soils could form, confined aquifer conditions would prevail. Provided the overall permeabilities of the soils and ash were adequate for the release of water from normal precipitation, only a limited water pressure would be present at any point on the hillside. During periods of intense rainfall such as occurred in early May 1998, however, water may percolate through the upper zones but be inhibited by the lower soil horizons. Where the overlying soils were sufficiently thick, water flowing downslope through the more permeable pumice deposits would be temporarily confined such that a hydrostatic pressure greatly in excess of the overburden would be created. A sudden failure would then take place as the pyroclastic material was moved outwards and downslope in a semi-liquid state.
6. The development of high hydrostatic heads may be exacerbated by initial localised failures where trees are uprooted. It has been noted that the roots of the horse chestnut and hazel nut trees generally extend only to shallow depths in order to obtain their nutrients from the pyroclastic deposits. When the upper soil horizons are broken, water can pass more readily into the pumiceous materials, accelerating the effects of high hydrostatic pressures. Trackways cut through the layered mantle deposits would again provide a quick access for water into the more permeable pumice layers.
7. The creation of the trackways around the slopes would produce an upslope angle significantly greater than that of the already steep gradient. An increase in water and hence weight in the upslope material would in itself be sufficient to cause mass failure, resulting in an arcuate feature developing above the trackways (Fig. 18). The failed material would then increase the loading on the

Fig. 18
Arcuate feature developed above a trackway

saturated volcanoclastic veneer on the lower slope, again causing deformation of the inherent soil structure leading to downslope failure.

8. Observations in gullies in which failures did not occur in May 1998 indicate a lack of bedrock outcrop. In some of these gullies the normal layering is preserved (Fig. 19). However in others, as described by Vallario (1992), following one failure there is likely to have been re-deposition of the loose surface veneer from further upslope as a result of creep and colluvial processes and the material has a chaotic appearance with no obvious layering. As a consequence of these processes there is likely to be a greater thickness of the volcanoclastic material within the gullies. Where the gullies are related to joints or faults, these would permit egress of water from the limestone bedrock into the floor of the gully. Under normal conditions, this water would be likely to percolate through the gully infill material and with time, cause the development of soil pipes within the re-constituted volcanoclastic deposits (Fig. 20).
   Such pipes would facilitate underdrainage at periods of low rainfall. However, at times of unusually high rainfall, particularly when preceded by a period of wet weather, the pipe system may be insufficient to permit full release of the increased ground water and raised perched water conditions would be created. As a consequence the additional egress would result in either a fast increase in the pipe capacity through erosion, the collapse of the pipe and the upward egress of water at the surface or the development of high pore pressures within the gully infill. If a collapse took place, resulting in an upwelling of water at the surface, fast surface flows would occur, similar to those reported in Quindici. If a collapse did not occur and the volume of water within the pipe system exceeded the capacity of the pipe, it would be forced into the interstices between the surrounding soil particles. With the hydrostatic pressures involved, the particles would separate such that the material would “float” and, with the sudden reduction in effective stress, mass liquifaction may occur.

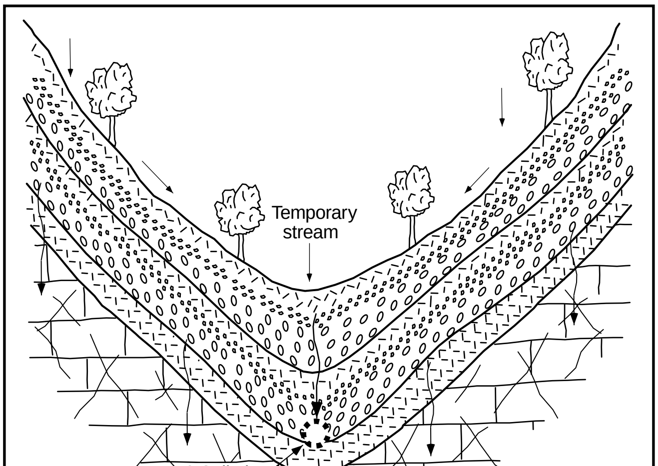


Fig. 19
Diagrammatic representation of typical layered deposits infilling a gully and likely position of a developing soil pipe; symbols as in Fig. 4

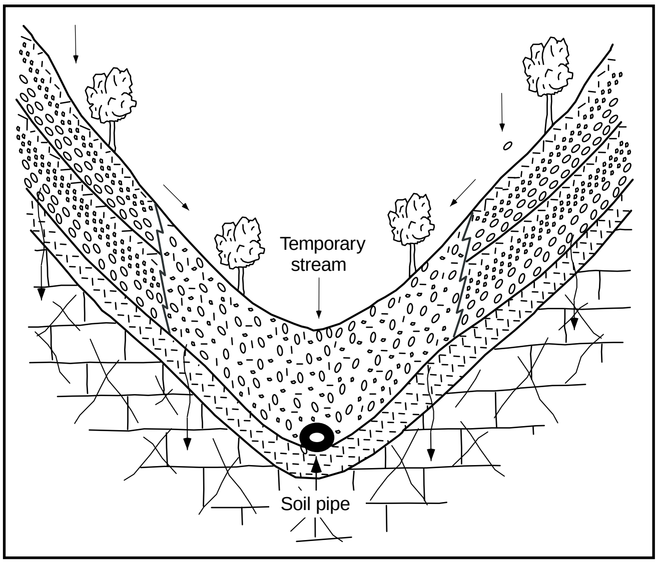


Fig. 20
Diagrammatic representation of re-constituted infill deposits and the development of a soil pipe in the base of the pyoclastic material; symbols as in Fig. 4

From the preliminary studies to date, it is likely that the shallow surface scars would not provide sufficient material to account for the large volumes present in the accumulation zones of the May 1998 event. As suggested by Vallario (1992), therefore, some of the material must have come from gully infill. In addition to the windblown/hillwash material infilling the hollows, thicker deposits may have accumulated locally behind temporary or permanent obstructions in the gullies. Such check dams could be created by fallen trees, by small landslips causing a temporary dam, by the lack of adequate drainage where man-made trackways cross the gullies and/or the presence of arrestor barriers which have been constructed towards the base of the slope in many of the gullies.

Fig. 21
Uneven nature of the limestone bedrock where thicker pyroclastic deposits accumulated in hollows

Discussion

Field evidence indicates that the mass movements described in this paper are the result of one or more of a number of scenarios. Although in each case the failures are undoubtedly triggered by rainfall, this may be in the form of a sudden, very high precipitation in a short period of time or cumulative above-average precipitation over a number of days. Detailed fieldwork is now being undertaken to establish the exact geometry, size and nature of each of the failures which occurred on 4/5 May 1998. Until this has been completed it is not possible to attribute a cause or failure mechanism to the individual landslips. A number of postulated scenarios are considered below.

Scenario 1: water egress from the bedrock

It is clear from field observations that the material involved in the mass movements is dominantly pyroclastic, although deposited by different eruptions. Layering can be identified in the thicker mantle materials, particularly where the airfall deposits accumulated in concave features on the surface of the limestone bedrock (Fig. 21). These natural breaks of slope within the dipping limestones are probably related to past slope failures, mainly toppling hence resulting in a step-like topography. Although impure bands have been identified within the limestones, such as that well exposed south of the road to the east of the town of Quindici (Fig. 22), to date insufficient fieldwork has been undertaken to confirm that these changes in lithology are responsible for the particular stepped nature of some of the hill slopes.

The presence of the less calcareous rocks is important as these will be less brittle and hence are likely to have a different discontinuity pattern from the very strong, brittle limestones. Although both the limestones and the impure bands (mudrocks) will have secondary permeabilities, dissolution through the limestone lithologies will have preferentially enlarged the tectonically induced fractures particularly above lower permeability bands. Weathering of any mudrocks would tend to cause expansion of the contained clay minerals, however, thus reducing the influence of their secondary permeability.

In addition, the difference in strength of the two materials will result in the discontinuities having slightly different orientations relative to the imposed stress. As a consequence, it is likely that water passing freely downwards through the limestones would have a lengthened flow path at an impure limestone/mudrock band such that a reduced permeability would be apparent. With normal rainfall the downward percolation of water would not be sufficiently impeded to cause a significant perched water condition. During heavy rainfall, however, impedance of downward flow would result in lateral movement above the lower permeability band and the tendency for the water to find an egress point on the upper slopes of the hillside.

The significance of these impure bands is difficult to assess in the field. In limestone bedrock the marly bands have frequently been sufficiently squeezed near the outcrop that they are effectively unrecognisable compared with the clearly defined horizons encountered when boreholes are drilled some metres behind the rock face. The hydrogeological influence of these bands is undoubtedly significant, but without detailed borehole evidence it is not possible to

Fig. 22
Impure limestone/mudrock band in the Mesozoic limestones east of Quindici

fully evaluate the contribution of these horizons to the formation of the steps within the limestone terrain and indirectly to major mass movements such as occurred on 5 May 1998.

As seen in the field, some of the joints in the limestone have not only been widened by dissolution but have also dilated at the surface such that the openings are now 10–20 mm wide. Such dilated, almost vertical joints in the near surface limestone bedrock would provide natural passageways in which water would accumulate when the downward percolation was impeded and egress was inhibited by the low permeability cover soils (Celico et al. 1986; Celico and Guadagno 1998). Whilst in normal conditions this would merely delay the passage of water, during periods of more intense and/or prolonged rainfall the water level within the limestone joints may rise sufficiently for the pressure to be greater than the restraining force of the overlying slope materials, resulting in sudden "outbursts".

This scenario, particularly likely in dipping strata, would explain the sudden increase in water flow observed in Quindici followed by the large movement of material in a fluidised state.

Scenario 2: Hydrostatic pressures within the pumice layer

As described above, the volcanoclastic deposits on the general hill mass are layered, the thickest bands being formed of pumice fragments. Grain size analyses of the pumiceous material typically found in this region and representing three separate eruptions indicate that some 85% is of sand or gravel size and up to 5–10% of clay or silt size (Fig. 23). In their undisturbed state the pumice layers are graded, with the finer silt and clay size fraction forming the later deposits. Between eruptions, soils developed on these upper finer materials and a clear palaeosol can be seen in many exposures. Above this a further thin pumice layer is present on which the modern soil has formed (Fig. 4). In some localities the clearly defined pyroclastic materials rest on an old soil which was undoubtedly derived in part from previous ash deposits. This soil varies in colour depending on its humic content and laboratory analysis has shown it to contain allophane.

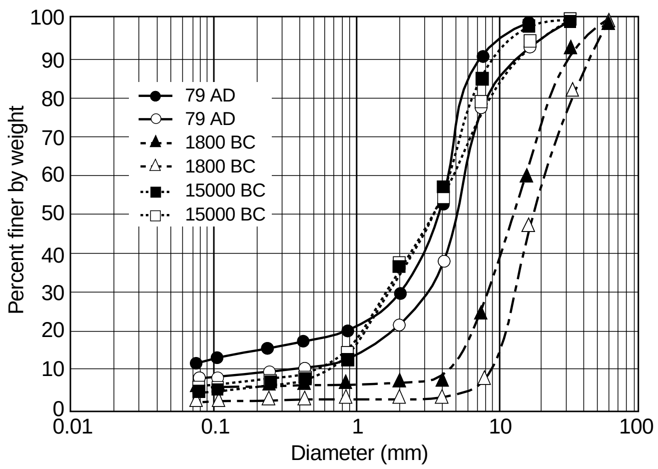


Fig. 23
Particle size distribution curves for the pumiceous deposits from three different eruptions

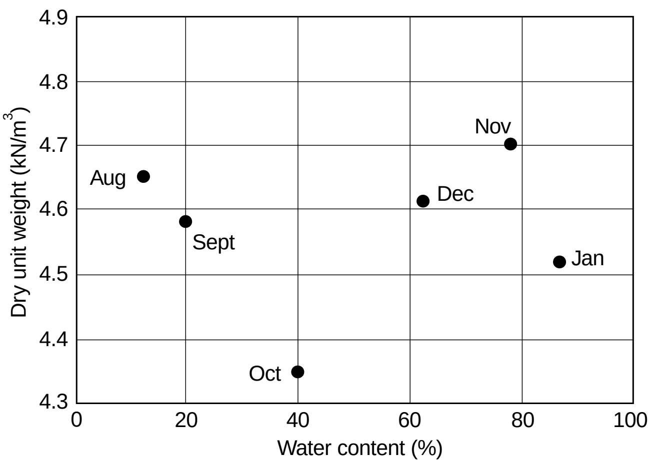


Fig. 24
Dry unit weight of pumiceous material sampled from the same unit between August and January indicating the seasonal change in water content

Experimental work by Esposito and Guadagno (1998a, b) has shown that the dry unit weight of the pumice is inversely related to the grain size. When the pumice fragments are more than 10 mm in size, the dry unit weight is only some 6.2 kN/m^3. These authors have also taken field samples using the sand replacement method to determine volume and have shown that the water content of the soils varies between 15 and 90%, although they appreciated some free water will undoubtedly have been lost during the sampling process. Esposito and Guadagno also undertook water content determinations on samples from the same pumiceous layer each month from August to January and showed that in summer the pumiceous material effectively dries while in winter it has a water content exceeding at least 60% (Fig. 24). No samples were tested during the main summer period. However, it is likely that in May, with the oncoming of the dry season and associated evaporation and evapotranspiration the water content of the pumiceous material would be less than 40%, although the finer fraction and any soils may have a higher water content. Following intense rainfall or consecutive days of above-average precipitation resulting in a significant cumulative total, percolation into the pumiceous layer would rapidly increase the water content. It is well known from flotation tests that the dry unit weight of the pumice is such that initially it will float until it slowly saturates when the contained water increases the density above that of water and the pumice sinks.

In areas where the pumice material is thickest, particularly in the concavities within the stepped limestone topography, a sudden intake of water by the pumiceous mass permits the inter-particle water conditions to change suddenly

Fig. 25
View of the northern side of the P.zo d'Alvano showing outcrops of vertical faces of limestone on a hill slope generally mantled with volcanogenic materials

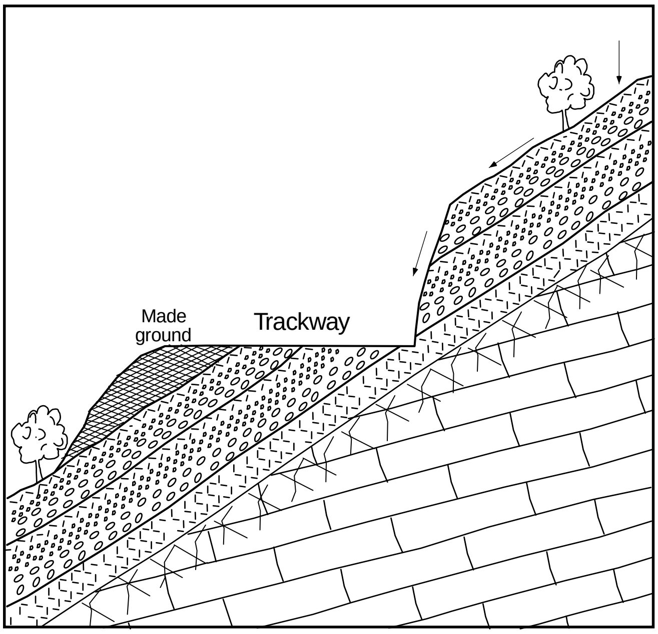


Fig. 26
Schematic cross-section showing the deposits likely to be exposed when a significant trackway is cut through the pyroclastic cover and the excavated material pushed downslope (see also Fig. 8); symbols as in Fig. 4

at a time when the intra-particle voids are still air-filled. If water percolating through the volcanoclastic mantle was impeded by the presence of one or more relatively low permeability palaeosols, the water would move laterally downslope through the lower pumiceous layer/s and hydrostatic pressures in excess of the local overburden pressure would develop. This increased hydrostatic pressure would be capable of lifting the air-filled pumiceous material. It is noted that in many locations the upper part of the mass movement started immediately above an outcropping thickly bedded limestone band where a stepped topography is evident. It is in these hollows that the thicker deposits of pumiceous material accumulated, providing ideal conditions for the development of Scenario 2.

Once the initial instability, created high in the hillside, had moved material forwards, it would fall over the limestone face and onto the deposits beneath. As this material on which it would fall is already in a metastable state, at or near limiting equilibrium, it would suddenly experience an undrained loading and a collapse of the natural fabric. In these conditions, this lower material would become effectively fluidised and behave in a similar manner to that discussed by Hutchinson (1986), Sassa (1998), Sassa et al. (1996) and Fleming et al. (1989). In some areas there are a number of near vertical limestone faces within the hill slope (see Fig. 25). Here a chain reaction would be set in motion as the upper slope material passed downward, ever increasing the load on the lower material and thus enhancing its mobility.

The downslope mobility of pumiceous-rich deposits would undoubtedly be increased where trackways have been cut across the slope (Fig. 26), exposing these materials. Without the normal surface soil horizon:

1. Rain would penetrate directly into pumiceous layers exposed in the trackways.
2. The exposed pumiceous materials would accept normal downslope surface water flows due to their higher permeability.
3. With high rainfall, downslope surface water would be intercepted by the trackways and channelled laterally along these pathways. As a result water from larger areas would be diverted along the trackways to produce streams of water which would preferentially sink into any exposed coarse grained pumice material.

Such localised concentrations of water with hydrostatic heads significantly above normal overburden pressure would readily create the type of instability seen in the field.

Scenario 3: failure in the palaeosols

The lowest palaeosol is dominantly a fine material with 80% less than 2 mm (Fig. 27). This material is known to contain allophane which in its saturated state has a low shear strength. Under relatively dry conditions any overlying pumiceous material will have a low density and the slope will remain stable. When a trackway has been cut through these materials, however, the lower palaeosol may be exposed, removing downslope support and thus creating a greater potential for slope instability (Fig. 26). Maeda et al. (1977) noted that the liquid limit of allophane rises from 120% with an initial water content of 20% to 180% when the clay mineral is fully saturated, indicating a probable significant reduction in shear strength. In addition, in sudden wet conditions there would be a very rapid rise in the free water content within the soil, such that the particles would become separated and the effective stress of the soil mass reduced. Once the effective stress had been lowered, the particles would become disturbed and lose the open texture typical of soils created in airfall deposits. Un-

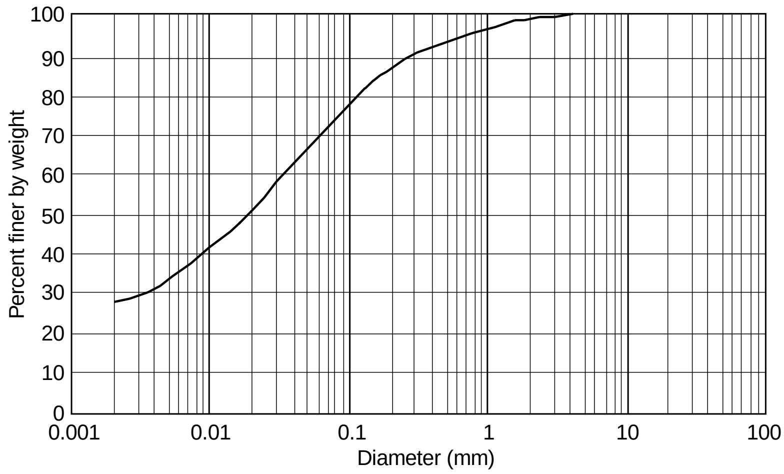


Fig. 27
Particle size distribution curve for the palaeosol through which the slope movements are most likely to have taken place

der such conditions, the slope would become unstable, particularly when any pumiceous materials had themselves become saturated hence of greater density. If failure occurred upslope, the material would move rapidly into the trackway and by loading the material downslope, initiate a chain reaction similar to that discussed above.

Scenario 4: gully failure

The above scenarios do not adequately explain the fact that although the 1998 failure/mass movement of material took place dominantly within the gullies, it did not occur in all of them. It is assumed that within any general locality a volcanic event would initially deposit approximately the same thickness of material over the whole mountain slope. Although wind and hill wash may result in a relatively increased thickness in hollows, the layered nature would still be largely retained. It is recognised that subsequently some thickening of the superficial deposits within the gullies is likely to have taken place as a result of normal hill slope movement and that following valley side failure, the remaining exposed mantle materials would be more prone to movement by wind or water. As a consequence, the gullies may contain thickened reconstituted material which will have different properties from the layered deposits.

It is likely that the gullies are located along zones of tectonic weakness (faults/joints), although this would be difficult to prove in the field in view of the vegetation and soil cover. Such zones are invariably the site of preferential dissolution and hence are likely to provide egress points. In view of the relatively high permeability of the pumice units, under normal rainfall conditions and where the deposits are layered (Fig. 19) any egressing water would probably be able to escape, although even in this situation some ground water piping may develop. Again, with normal precipitation, water moving from the bedrock into the gully infill material would pass downslope within these disturbed sediments. Without the presence of the more permeable pumice layer, however, the percolation pathways would progressively create a natural soil pipe (Figs. 20, 21). Elsewhere such natural pipes are known to be up to some 500 mm in diameter and hence have the capacity to move significant volumes of water.

Occasionally local collapse occurs within a pipe. Under normal rainfall conditions the collapsed material would be gradually removed and the pipe re-establish its flow potential. When the ground water flow is suddenly increased, however, the collapse material interrupts the flow, creating a turbulent situation when rapid erosion/chimney action takes place and the water bursts through to the surface. Such weakened soils within the gully may then become unstable and move downwards in a semi-fluid manner, exacerbated by the additional weight of the disturbed upslope material. Alternatively, a sudden inrush of water from the bedrock can result in the flow capacity of the pipe being exceeded such that water percolates outwards into the surrounding re-deposited material. Such a situation would lead to a sudden reduction in effective stress, a lowering of the shear strength and a failure of the gully infill, similar to the process of fluidisation.

Conclusions

The air fall materials from the various eruptions of Somma Vesuvius were generally blown to the south and east and now form a mantle over the Cretaceous limestone massifs. Prior to the volcanic activity the limestone hills were experiencing block failure along the slopes and karstic erosion while at the surface, some soil development took place. When the pyroclastic materials fell onto this irregular topography, the hollows were infilled with deeper deposits.

The airfall deposits consist of graded pumice layers and ash, the lower coarser pumice having grain size diameters of 10–15 mm. During periods of quiescence, soils were formed on the upper fine grained materials by natural pedological processes.

Following a period of heavy rainfall, the 58 mm which fell on 5 May 1998 triggered a large number of slope failures around the P.zo d'Alvano hill mass. As a consequence of the large volume of material which moved downslope in a very short period and extended into the towns of Quindici and Sarno, there was significant destruction of buildings and more than 161 people lost their lives.

A series of scenarios and possible failure mechanisms have been considered:

1. The influence of low permeability horizons in the limestones creating temporary rises of the perched water conditions, resulting in localised egress points and uplift pressures on the underlying loose pyroclastic cover.
2. The metastable condition of the light weight pumice, ash and palaeosol materials. These would fail readily in a wet state or if short term confined water conditions were created as a result of unusually heavy or prolonged rainfall. The thicker deposits in the stepped hollows would be particularly prone to failure under such conditions while movement of this material would induce undrained loading further downslope, especially when it fell over vertical limestone faces.
3. The influence of the trackways created in the last 20 years to facilitate vehicle access into the nut plantations on the hill slopes. Such trackways not only have steep upslope faces and loaded downslope conditions, they also form linear features in which streams can collect downslope surface run-off. The exposed pumiceous material would provide sinks into which the temporary streams could flow, raising the downslope "confined water" to hydrostatic pressures greatly exceeding that of the overburden.
4. Gully failure resulting from either collapse of an underground pipe system which normally discharges the water from the hill slope or to the pipes being of insufficient capacity to accommodate the unusually high water flows. In the former, turbulent flow would cause sudden erosion and resultant instability while in the latter, high pore pressures created adjacent to the pipes by the high hydrostatic heads would reduce the inter-particle contact such that the infill material would in effect flow as a liquified mass.

Whilst undoubtedly the rainfall was a dominant factor in all of the failures, one or more of the scenarios discussed may have caused the individual mass movements. Further work is being undertaken to elucidate the causes of the individual failures and it is anticipated the results will be published in the near future.

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