Available online at www.sciencedirect.com
ScienceDirect
Geomorphology 87 (2007) 132–157
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Slope processes in weathered volcaniclastic deposits within the city of Naples: The Camaldoli Hill case

D. Calcaterra [a], D. Coppin [a], S. de Vita [b], M.A. Di Vito [b], G. Orsi [b], B. Palma [a], M. Parise [c,*]

[a] Section of Applied Geology, Department Geotechnical Engineering, Federico II University of Naples, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Naples, Italy
[c] National Research Council, IRPI, Via Amendola 122-I, 70125 Bari, Italy

Received 6 August 2004; received in revised form 23 July 2005; accepted 24 March 2006
Available online 6 October 2006

Abstract

We describe the slope processes acting on Camaldoli Hill, the main volcanic feature of the Neapolitan area whose geological evolution and setting have been reconstructed. The backbone of the hill includes the remnants of two partially superposed tuff cones, lying between the Campanian Ignimbrite (CI) and the Neapolitan Yellow Tuff (NYT). This sequence is mantled by pyroclastic, anthropogenic and epiclastic deposits, with abrupt thickness and facies variations. The structural setting of the hill mainly results from several phases of reactivation of the CI caldera faults which were active until about 9.5 ka. Deformation younger than 15 ka is evidenced by landslide deposits, caused by slope instability from volcano-tectonism, and by a high-angle erosional unconformity, formed in response to a base-level lowering. A stratigraphic analysis of the reworked deposits at the foot of the slopes allowed us to define both depositional mechanisms and sedimentation rates. The results of combined volcanological, geomorphological and engineering-geological studies permitted us to constrain and quantify past geological processes and hypothesis about the future evolution of the hill. Present-day slope processes on Camaldoli Hill are largely controlled by the presence of weathered and reworked deposits, whose nature and thickness have been analysed and mapped in detail. Four main kinds of slope processes have been recognized: falls and toppling failures from NYT; small-scale slides in the weathered and pedogenized loose cover; mixed events, represented by slides evolving to hyperconcentrated flows, mud flows and debris flows; and areal and linear erosion. Consequently, a high number of mass movements not previously documented have been mapped. At the same time, an insight into the sedimentation rate due to the overall slope processes, covering a time-span of about 5 ka, was given. Some final considerations regarding landslide hazard are presented in the context of the most suitable remedial works.

Keywords: Slope processes; Weathering; Volcaniclastic rocks; Hazard; Risk

1. Introduction

The complex interplay between the soil–subsoil system and the anthropogenic built environment in an urban area poses many difficult engineering-geological problems which have to be properly faced by humans. Especially in urban settings, where humans have resided

* Corresponding author. Tel.: +39 080 5929587; fax: +39 080 5929611.
E-mail address: m.parise@ba.irpi.cnr.it (M. Parise).

0169-555X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.03.040

since early historical times, these factors play a paramount role. The city of Naples was founded in the VII century BC, and represents a typical example of a stratified city. Since the foundation of Naples human activity has deeply modified the local environment: as a consequence, the remarkable expansion of the city in the last four centuries caused underground cavities and infrastructure, sewage network, and retaining works to be among the main sources of technical problems. All of this is currently emphasized by a population density (more than 9000 inhabitants/km^2) among the highest in the world. To these aspects, slope instabilities need to be added because vast portions of the metropolitan area of Naples are characterized by hillslope morphologies (Fig. 1).

Recent and repeated episodes of slope movements at Naples and other sites in Campania (January 1997, May 1998, September 2001, April 2002, December 2004 and March 2005, only to cite the most important) created an awareness of the landslide hazards in the region, and pushed earth scientists, land planners and decision makers to undertake research aimed at evaluating the hazard and at mitigating the related risk. In this regard, it has to be noticed that the Italian government, through local authorities, has declared the city of Naples, with a special emphasis on the Camaldoli hill, a national priority in terms of landslide risk mitigation.

This paper examines the Camaldoli hill, the highest ridge within the inhabited Neapolitan area at 458 m a.s.l., with particular reference to its western slope, just above the densely populated district of Pianura. The presence of morphologies typical of the whole Neapolitan area, and the occurrence and frequency of a variety of slope movements, combined with the proximity to a densely urbanized area, still in expansion, makes the Camaldoli Hill a suitable site of analysis for landslide hazard assessment in the metropolitan area of Naples.

The western slope of the hill has been studied by combining stratigraphic and geomorphological analyses. The first were focused at defining the exposed volcaniclastic deposits, their geometrical relationships, the nature and genesis of the surfaces separating them, and their main weathering products. Facies analyses allowed also to define the transport and depositional mechanisms. These analysis were integrated with results from subsurface explorations (boreholes and trenches) to define the sedimentation rate, and to discriminate between the intervals deriving from water-laid processes and those produced by slope movements. Use of the drilled sequences was necessary, due to lateral migration of the depositional systems, which causes the calculated sedimentation rates to be representative only locally, and not be extendable to the whole sedimentation basin. The drilled sequences, on the other hand, are representative of longer time intervals, which allowed us to characterize depositional systems active at least over the past 2.0–3.8 ka. The sedimentation timing was defined using pyroclastic deposits of known age, archaeological findings and man-made structures.

The geomorphological analyses, on the other hand, made possible a zonation of the area in terms of morphological features, and a differentiation of the slope movements affecting each sector of the Camaldoli Hill. A variety of landslides occur at the site, which makes particularly difficult, even due to problems in accessibility to some sectors of the hill, any effort toward

Fig. 1. View of the western slope of the Camaldoli Hill, showing the inhabited area of Pianura on the basal plain. Note urbanization of the hill on the top highplain.

mitigation of the landslide risk through active measures. The spatial distribution of slope movements at the Camaldoli Hill defined in this study, as well as the maximum expected areas of invasion by landslide material, have recently been directly verified in the field on the occurrence of further episodes of slope movements, which have been registered in December 2004 and March 2005.

2. Geological setting

The Camaldoli hill (Fig. 2) is the north-eastern morphological boundary of the Campi Flegrei caldera (CFc), a restless, nested structure generated by two main collapses, related to the Campanian Ignimbrite (CI — 39 ka; De Vivo et al., 2001) and the Neapolitan Yellow Tuff (NYT — 15 ka; Deino et al., 2004) eruptions (Orsi et al., 1992, 1996). Volcanism in this area is related to Plio-Quaternary extensional tectonics that deformed the western margin of the Apennine chain and formed the graben structure of the Campanian Plain (Ippolito et al., 1973; D'Argenio et al., 1973; Finetti and Morelli, 1974; Bartole, 1984). The beginning of volcanism in the area is not precisely defined. The oldest dated rocks, which are not the lowermost in the stratigraphic sequence, yield an age of about 60 ka (Pappalardo et al., 1999) and are

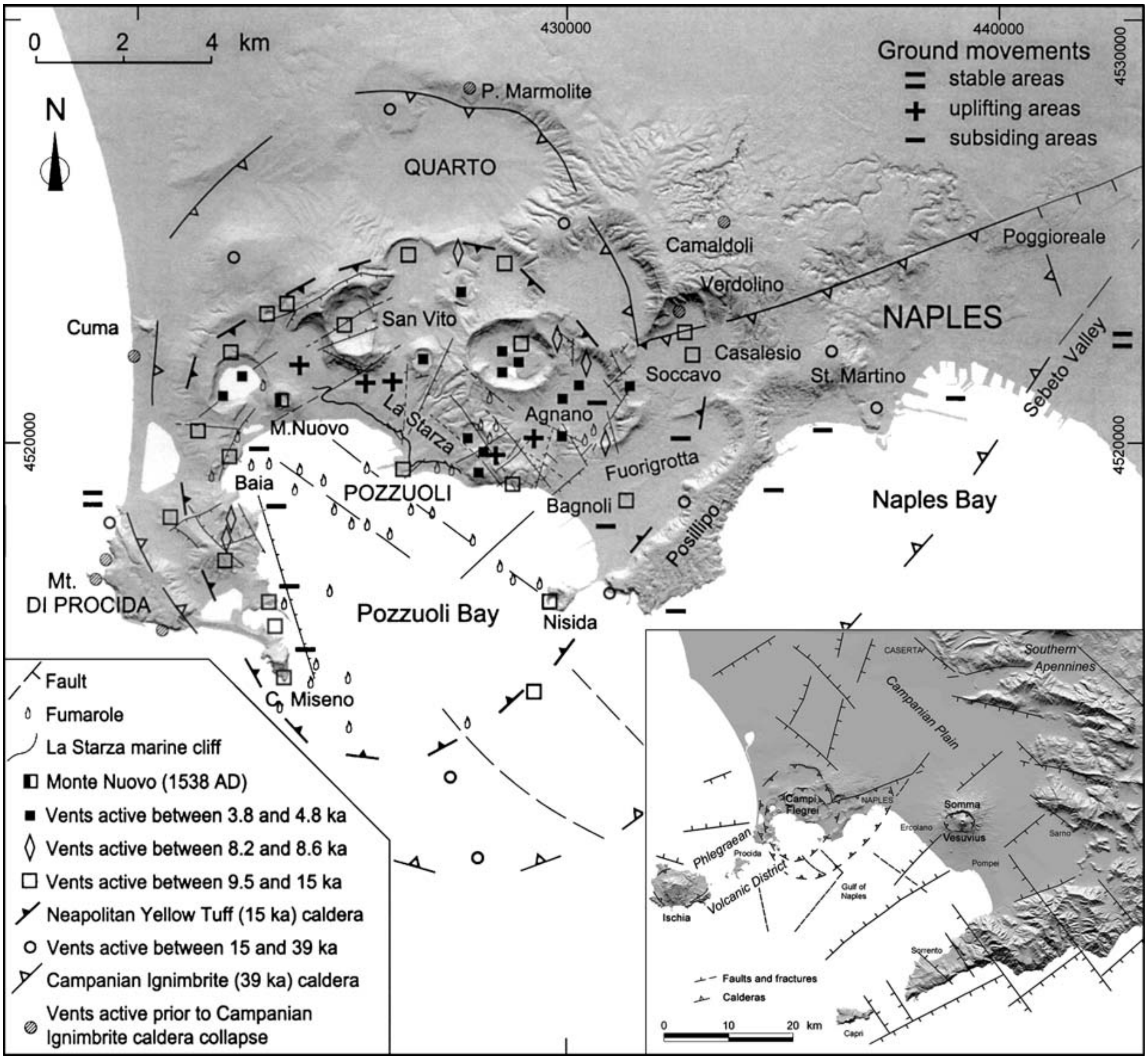

Fig. 2. Structural map of Campi Flegrei caldera.

related to explosive volcanism which extended beyond the present CFc margin. The complex shape of the CFc results from an interplay between constructive volcanic and destructive volcano-tectonic events. Sea level variations also greatly contributed to the present morphological setting.

The first event that strongly influenced the geological and structural evolution of the area is the

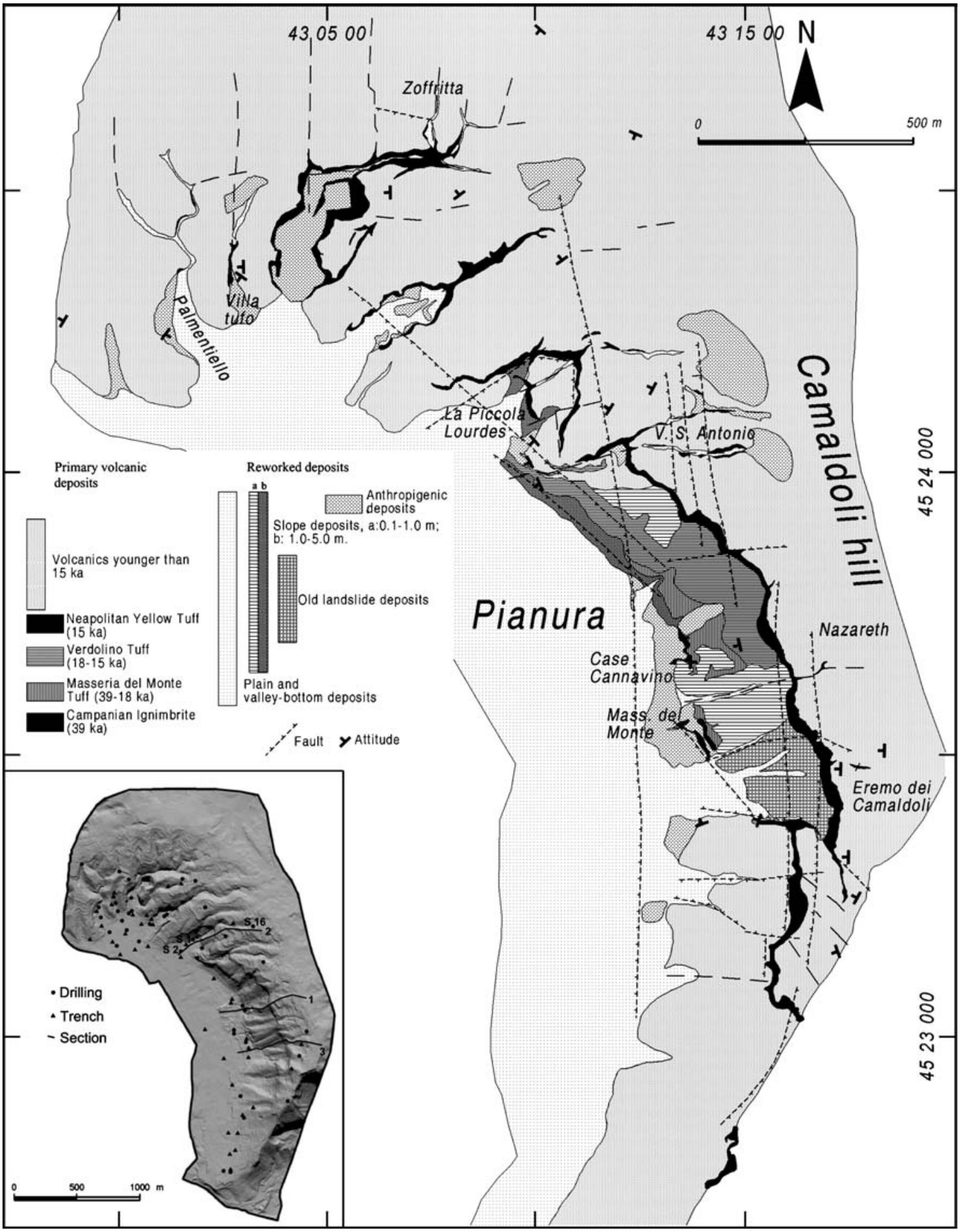

Fig. 3. Geological map of the study area. In the inset locations of boreholes, trenches, and cross sections are shown.

Table 1
Description of stratigraphic units, listed from oldest to youngest

Unit	Stratigraphic position	General features	Vent area (volcanic edifice)	Genetic process
Campanian Ignimbrite (CI)	The base is not exposed in the mapped area, while it is unconformably overlain by all the younger units	Sequence of variably welded blackish, flattened scoriae, in a light-grey ash matrix (Piperno), locally conformably overlain by a coarse, polygenetic and eterometric breccia (Breccia Museo) and a low-grade, reddish-grey ignimbrite. Subvertical degassing pipes are common within Breccia Museo and Piperno. The whole sequence is almost horizontal or gently eastward dipping. Although the maximum exposed thickness is about 20 m, geometrical restoration allows to estimate a maximum value of about 70 m.	Campi Flegrei caldera	Caldera-forming eruption
Masseria del Monte Tuff	It overlies a westward dipping erosional unconformity or a poorly developed paleosol above CI. At Masseria del Monte, it mantles a high-angle unconformity cut in the Piperno. Unconformably overlain by younger deposits.	Poorly lithified, strongly laminated, greyish-white sequence of plane-parallel to cross-stratified ash beds with pumice layers and lenses, gently westward dipping. Pumice fragments are greyish-white, subangular, well vesiculated and porphyritic with feldspar and biotite phenocrysts. Impact sags indicate easterly provenance. The sequence, intensely fractured, attains a maximum thickness of 50 m at Masseria del Monte.	Remnant of a tuff cone, whose vent was likely located in the area of Soccavo.	Phreatomagmatic eruption
Verdolino Tuff	It lies above a high-angle unconformity cut into the Masseria del Monte Tuff and CI deposits. Overlain by the NYT (15 ka), and locally by slope deposits thinner than 0.5 m.	Plane-parallel to cross-stratified sequence of ash layers containing pumice and lithic fragments. Pumice fragments, both angular and sub-rounded, are well vesiculated, grey and porphyritic with phenocrysts of feldspar and subordinate biotite and pyroxene. Lithic fragments are lava clasts. Impact sags indicate provenance from the eastern quadrants. The tuff, usually yellow and zeolitized, east of Masseria del Monte shows a grey and poorly lithified base. Exposed along the entire Camaldoli hill slopes (maximum thickness about 50 m at Masseria del Monte), it generally dips towards the W–NW, and is intensely fractured.	Remnant of a tuff-cone, whose vent was likely located in the Soccavo area	Phreatomagmatic eruption
Neapolitan Yellow Tuff (NYT)	It unconformably lies above all the older deposit and is unconformably overlain by all the younger deposits	Strongly zeolitized succession of massive-to-laminate ash layers of contrasting grain-size, with scattered pumice and lithic fragments (Upper Member; Orsi et al., 1992) forming steep cliffs in the upper portion of the hill slopes. An alternance of loose-to-cohesive, thin fine-ash beds and pumice layers (Lower Member; Orsi et al., 1992), not thicker than few meters locally occurs in the lower part of the sequence. The tuff varies in thickness from a few tens of meters, near the top of the hill, to about 100 m in the area of the Zoffritta quarries. Cooling fractures as well as joints and fractures, associated with the main fault systems affecting the Camaldoli hill, contribute to deformation of this unit.	Campi Flegrei caldera	Caldera-forming eruption

Table 1 (*continued*)

Unit	Stratigraphic position	General features	Vent area (volcanic edifice)	Genetic process
Old landslide deposits	These deposits are eteropic with the Plain and valley-bottom deposits. Overlain by paleosol B.	Mainly m-sized blocks of NYT supported by a fine-to-coarse sand matrix forming lobes along the steep slopes between Eremo dei Camaldoli and Nazareth. Morphological evidence suggests that the thickness could vary between a few and a few tens of meters.		Mass movements generated by fall-toppling coupled with debris sliding mechanisms
Volcanics younger than 15 ka	The sequence unconformably mantles the older units and is overlain by the younger deposits.	Sequence of pyroclastic deposits and paleosols. Pyroclastic rocks are mainly fallout and subordinately surge deposits, composed of ash and lapilli sized pumice layers. Ash beds are variably cohesive and contain accretionary lapilli, scattered pumice and lava and tuff lithic clasts. Pumice layers, usually well sorted, contain a variable amount of lithic fragments and vary in thickness from few centimeters to tens of centimeters. Paleosols, usually developed on ash or reworked deposits, show variable degree of humification. The entire sequence varies in thickness between few and 30 m. Locally it has been reworked for terrace-cultivation and building construction.	NYT caldera	Phreatomagmatic and magmatic eruptions
Plain and valley-bottom deposits		Sequence of sand and silt layers and lenses, containing variably sized pumice, lavas and tuffs fragments, and, locally, manufactured goods of variable age. Layers are loose and well sorted. Lenses usually have concave base and flat top, and vary in amplitude from a few tens of centimeters to few meters. The sequence is composed of regular successions of coarse sand, fine sand and silt, from base upwards. Each succession shows a basal erosional unconformity. Locally, at the main valley outlets, the sequence is interbedded with massive, poorly sorted, slightly cohesive and vesiculated silty-sands deposits thinner than 0.1 m. Total thickness of the unit, very variable according to local paleomorphology, is comprised between 0.5 and 5 m within valleys, and more than 5 m at the footslopes. This unit has been locally reworked to make terraces for agricultural and building purposes.		Water-laid and flood episodes, intercalated with hyperconcentrated flows
Slope deposits	Unconformably mantle all the older units	Chaotic deposits composed of tuff blocks of variable shape and size (0.1 m to few meters), with a fine-to-coarse sand matrix. The thickness of this unit does not exceed 1 m along the steep slopes between Masseria del Monte and Piccola Lourdes, and varies between 1 and 5 m at the foot of the slope between Piccola Lourdes and Case Cannavino.		Surface alteration and humification of the Masseria del Monte and Verdolino Tuffs and erosion of the overlying NYT and Pyroclastic deposits younger than 15 ka.
Anthropogenic deposits		Chaotic deposits composed of etherometric blocks of tuffs, lavas, concrete, pottery, and a variable amount of manufactured goods of industrial age, in a fine-to-coarse sand matrix, usually produced by		This unit includes all the deposits generated by the accumulation of

(continued on next page)

Table 1 (*continued*)

Unit	Stratigraphic position	General features	Vent area (volcanic edifice)	Genetic process
Anthropogenic deposits		the destruction of the component blocks. They usually lie at the bottom of open-cast quarries or at the exit of underground quarries, and both along the slopes and at the valleys bottom. The thickness, very variable depending on the local paleomorphology, never exceeds 5 m. In quarries at valleys outlet, often recent alluvial sediments are interbedded within the sequence.		discarded materials, produced by quarrying and building activities

CI eruption. This eruption extruded at least 200 km^3 of magma (Fedele et al., 2003) and was accompanied by the collapse of a 230 km^2 wide caldera, which includes the city of Naples, the Campi Flegrei, and part of the Naples and Pozzuoli bays (Fig. 2). The pyroclastic rocks, mainly formed by dilute and turbulent pyroclastic currents covering an area of about 30,000 km^2, greatly modified the landscape. The currents were able to surmount a topographic barrier higher than 1000 m, towards the north and the east, and to flow as far as the Sorrento peninsula, to the south. After the CI eruption, between 39 and 15 ka, volcanism was concentrated within the collapsed area and produced mainly explosive and subordinately effusive eruptions that generated poorly dispersed pyroclastic deposits, tuff-cones and lava domes.

The NYT phreato-plinian to phreato-magmatic eruption occurred at 15 ka. During this eruption at least 40 km^3 of magma were erupted and a 90 km^2 wide caldera formed within the earlier CI caldera. Pyroclastic-currents and fallout deposits were emplaced over an area of about 1000 km^2, mainly north-east from the source. Although the CFc is generally subsiding, an ongoing resurgence affects the central portion of the NYT caldera, and has generated in the past 15 ka a maximum net uplift of about 90 m (Orsi et al., 1991, 1996). Not less than 70, mainly explosive, eruptions have occurred within the NYT caldera, concentrated in three phases of activity

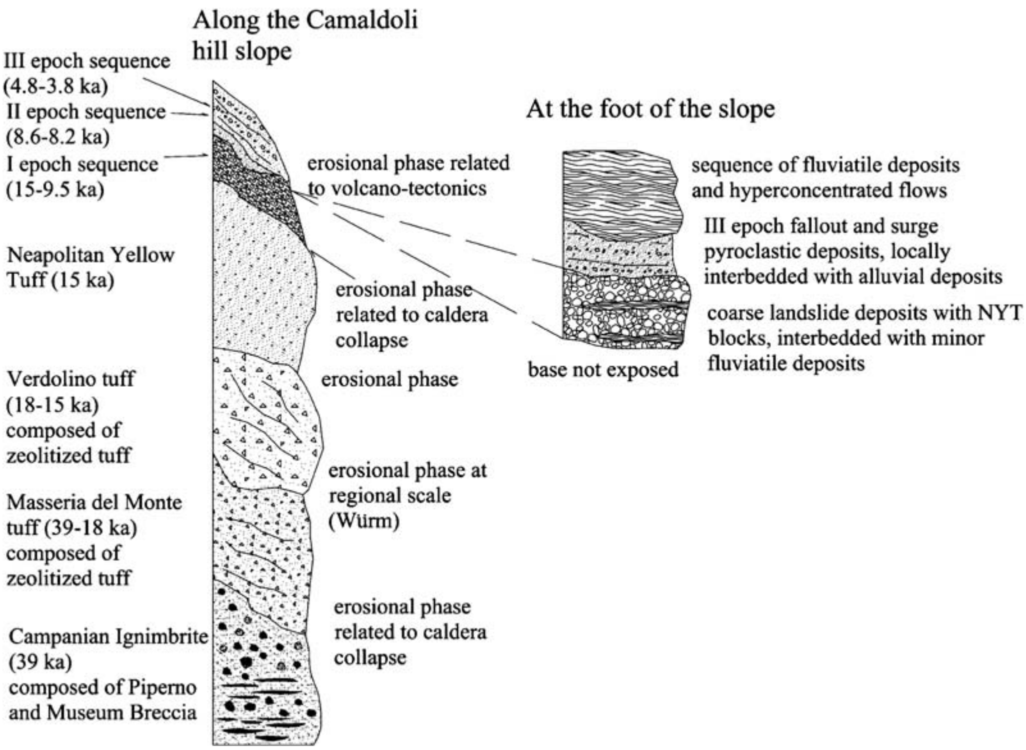

Fig. 4. Reconstructed, generalized, stratigraphic sequence of the Camaldoli hill.

separated by two periods of quiescence (Di Vito et al., 1999), evidenced by two widespread paleosols, named A (9.5–8.6 ka) and B (8.2–4.8 ka), respectively. The last eruption occurred in 1538 AD, after a 3 ka long period of quiescence, and formed the Mt. Nuovo tuff cone (Di Vito et al., 1987). In the past 35 years the CFc has been affected by several unrest episodes with a net uplift of about 3 m (Orsi et al., 2004 and references therein).

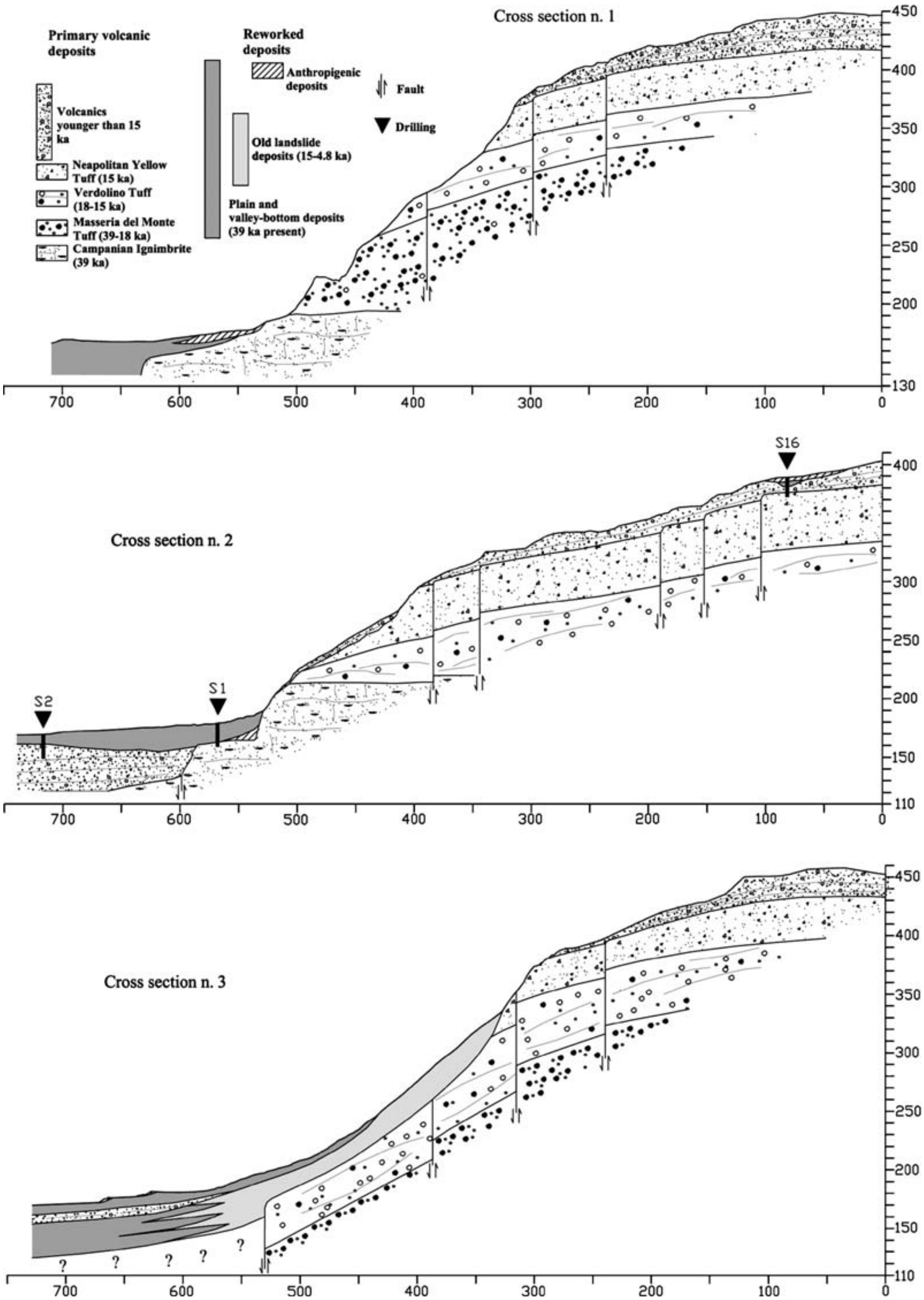

Fig. 5. Geological sections.

Volcanism and volcano-tectonism in the past 39 ka greatly contributed to the present morphostructural setting of the Neapolitan–Phlegraean area. Eruptions built a large number of monogenetic volcanoes, the youngest of which are well preserved. In some cases the original volcanic morphologies have been moulded or partially dismantled by tectonic and volcano-tectonic events, and intense erosional and deposition processes of pyroclastic deposits. One of the main morphological features of the CFc is the large number of coastal and internal plains, located at variable elevation and related to volcanic and volcano-tectonic deformation events. Some depressions within the NYT caldera have been periodically submerged by the sea, as demonstrated by type of sediments and presence of depositional or erosional landforms (i.e. marine terraces, sea cliffs). General subsidence of the CFc and resurgence of the central portion of the NYT caldera also contributed to the complex morphology of the area. In particular the 458 m high Camaldoli hill, which dominates the Phlegraean landscape, is the result of a complex interplay between deformation events, such as the CI and NYT caldera collapses, and constructive volcanic episodes younger than the CI eruption.

2.1. Geology of the Camaldoli hill

A detailed geological survey at 1:2000 scale of the western slopes of the Camaldoli hill has allowed us to reconstruct the stratigraphic sequence and the structural setting of the hill (Fig. 3). The field survey has been integrated with aerial photo (scale 1:2000) interpretation, and stratigraphical, sedimentological and mineralogical analyses of cores of 43 boreholes and of 40 trenches (Fig. 3). The recognized rock bodies include volcanic and non-volcanic sediments, the main characteristics of which are reported in Table 1, whilst their geometric relationships are shown in Figs. 3, 4 and 5. The stratigraphic sequence of the area was first reconstructed by Rittmann (1950). The lowermost unit is the CI, which includes the Piperno, Breccia Museo, and ignimbrite members (Barberi et al., 1978; Fisher et al., 1993; Civetta et al., 1997). This sequence, almost horizontal or gently dipping eastward, is exposed in the area of Piccola Lourdes, at Masseria del Monte and at Case Cannavino, where it was intensively quarried until the beginning of the XXth century. Rittmann (1950) included the pyroclastic rocks of the area, emplaced between CI and NYT, in a unit named *Tufi Biancastri* (Italian for Whitish Tuffs). Orsi et al. (1996), based upon recognition of paleosols and erosional unconformities, subdivided the sequence in five units, each related to a different eruption, and named them VRa through VRe, from base upwards. In the mapped area, only units VRb and VRe have been found and herein are named Masseria del Monte Tuff and Verdolino Tuff, respectively. These two sequences are remnants of tuff cones. The Masseria del Monte tuff cone has been deeply eroded during the last glacial lowering of the base level (18–14 ka), therefore its age is bracketed between 39 and 14 ka. The Verdolino Tuff lies above a high-angle unconformity cut into the underlying Masseria del Monte Tuff and Campanian Ignimbrite, and is in turn overlain by the NYT (15 ka). Therefore its age must be between 18 and 15 ka.

Old landslide deposits are constrained between the NYT at the base and the Paleosol B at the top. Very likely these landslides were induced by intense deformation events between 15 and 8 ka.

The sequence named Volcanics younger than 15 ka includes the deposits of a large number of the CFc eruptions younger than NYT. Volcanism and related products, as well as deformation of the caldera, have been recently described by de Vita et al. (1999), Di Vito et al. (1999), Orsi et al. (1999, 2003) and Isaia et al. (2004). Paleosols A and B, which separate the deposits of the three epochs, have been used as marker layers as they are widely distributed over the entire Neapolitan area.

Plain and valley-bottom deposits, and slope deposits, are generated by surficial processes which affect all the exposed rocks. The Anthropogenic deposits result from the thousands-of-years long presence of humans in the area (Orsi et al., 2003).

A thickness map of the loose deposits was elaborated (Fig. 6), based on stratigraphic and stratimetric data collected during field surveys, integrated with drilling and trench data (Figs. 3 and 4). These deposits, which are all younger than the NYT, have been subdivided in two groups according to their depositional mechanism. The first group includes the pyroclastic sequence, further subdivided in four thickness classes: class 1 = 0.0–0.5 m; class 2 = 0.5–1.0 m; class 3 = 1.0–5.0 m; class 4 > 5.0 m. The second group includes old landslide, slope, plain and valley-bottom deposits related to water-laid transport and slope movements, as well as anthropogenic deposits, subdivided in two thickness classes: class 5 = 0.5–5.0 m; class 6 > 5.0 m. Classes 4 and 6 are the most represented in the map of Fig. 6. Class 4 prevails near the top of the hill and along gently dipping slopes; class 6 dominates within the plain.

The Camaldoli hill is located along a N–S to NW–SE trending arched sector of the northern margin of the CFc. Deformation during the CI caldera collapse was

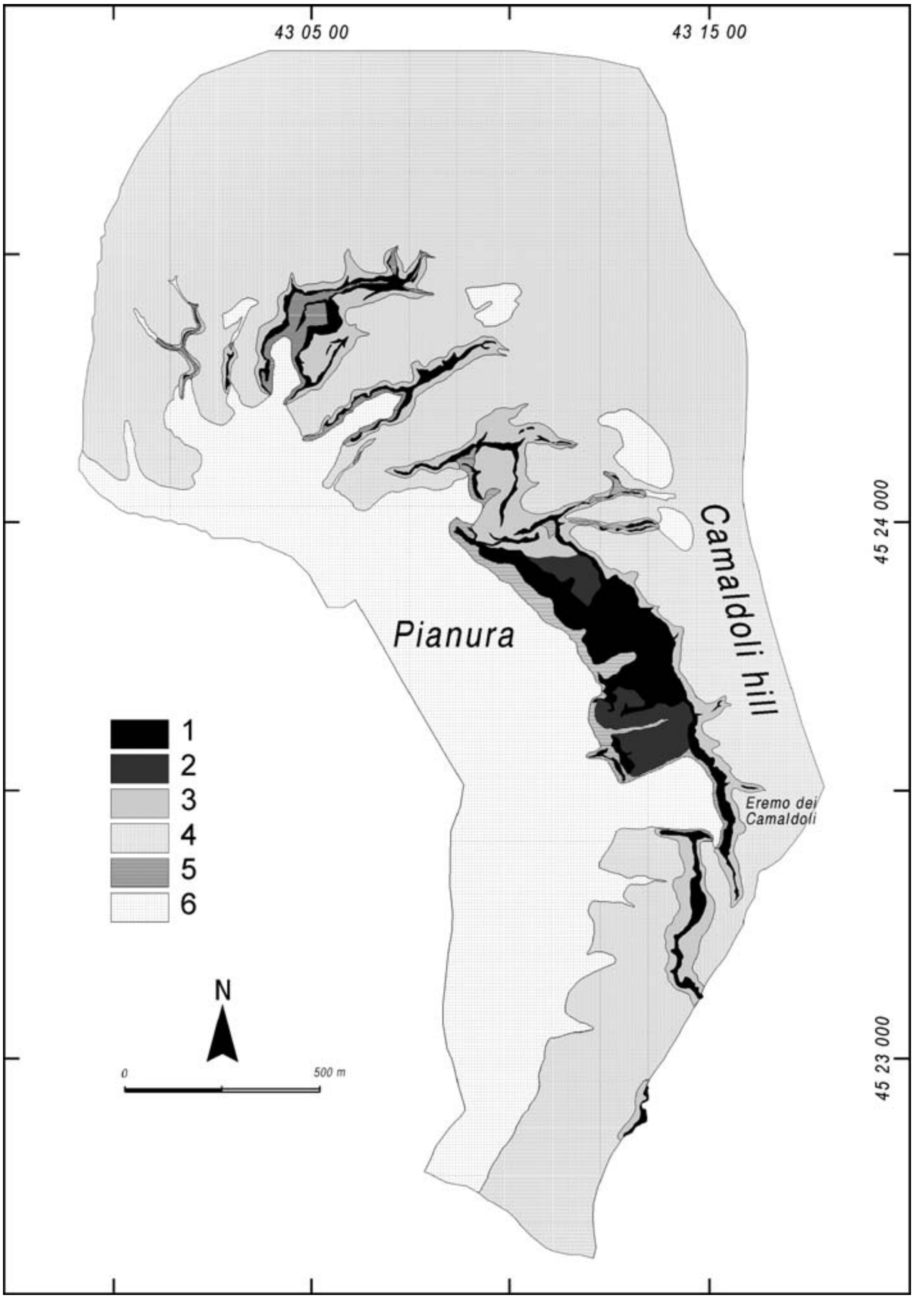

Fig. 6. Thickness map of loose deposits at the western slope of Camaldoli Hill. Pyroclastic sequences: class 1 = 0.0–0.5 m; class 2 = 0.5–1.0 m; class 3 = 1.0–5.0 m; class 4 > 5.0 m. Old landslide, slope, plain and valley-bottom and anthropogenic deposits: class 5 = 0.5–5.0 m; class 6 > 5.0 m.

accommodated by both activation of newly formed faults and reactivation of pre-existing NE–SW and NW–SE trending regional faults. All these features have been later reactivated during deformational events related to the NYT caldera collapse and by volcanic and volcano-tectonic activity of the first epoch of volcanism of the CFc (15–9.5 ka). The present structural setting is characterised by two main fault systems, trending N–S and N80E, and by a subordinate N40W system. The N–S system includes vertical faults, active at least between 39 and 15 ka, which downthrow to the west the units exposed along the western slope of the Camaldoli hill. The scarps exposed at the foot of the slope, bordering the Pianura plain to the east, result from the morphological evolution of fault planes. Along these planes, the largest displacement has been achieved by the westward downthrowing of the Piperno and Breccia Museo Members of the CI. Faults related to this system have generated maximum vertical displacements on the order of 10 m along the slope, and have progressively downthrown westward the NYT and the underlying sequence. Such a deformation has locally caused an apparent thickening or doubling of the exposed successions. This fault system is sutured by deposits younger than the NYT towards the north, where they attain their maximum thickness.

The N80E system crosscuts the N–S system generating differentially displaced blocks. The vertical displacement along each fault does not exceed 10 m. Deep fracturing of the rocks, caused by faulting, favoured the triggering of complex gravitational movements, which generated thick deposits of detrital material at the foot of the steepest slopes. This fault system is also sutured by the deposits of the past 15 ka and, in particular, by Paleosol B (8.2–4.8 ka) and a pyroclastic sequence of the third epoch (4.8–3.8 ka).

The subordinate N40W fault system was originated by partial reactivation of regional faults, which have been certainly active between the CI eruption and the first epoch of recent volcanism. Field evidence indicates that sequences including the NYT and older units were downthrown to the southwest by this fault system. The orientation of the slope between Piccola Lourdes and Masseria del Monte (Fig. 3) is inherently influenced by these structures, which also significantly deformed the NYT, located in the upper portion of the hill. The largest vertical displacement of about 10 m was attained along the faults activated between Eremo di Camaldoli and Piccola Lourdes. In adjacent areas the displacement did not exceed few meters.

The vertical displacement of all the faults never exceeding 10 m, results in minor offsets of the faulted rock bodies. Furthermore, as their activity is older than 5 ka, the offsets are generally masked by the pyroclastic deposits of the III epoch.

Minor, closely spaced and pervasive structures, such as joints and fracture cleavage in thin stratified rocks, are associated with the described fault systems. These features, resulting from brittle deformation, have generated an intense jointing in blocks, varying from tens of centimeters to tens of meters, mainly in the lithified rocks at the tops of the steepest slopes.

3. Geomorphological setting

The main morphological features of the western slope of Camaldoli Hill are represented by several subvertical cliffs, either of structural or erosional origin. In the latter

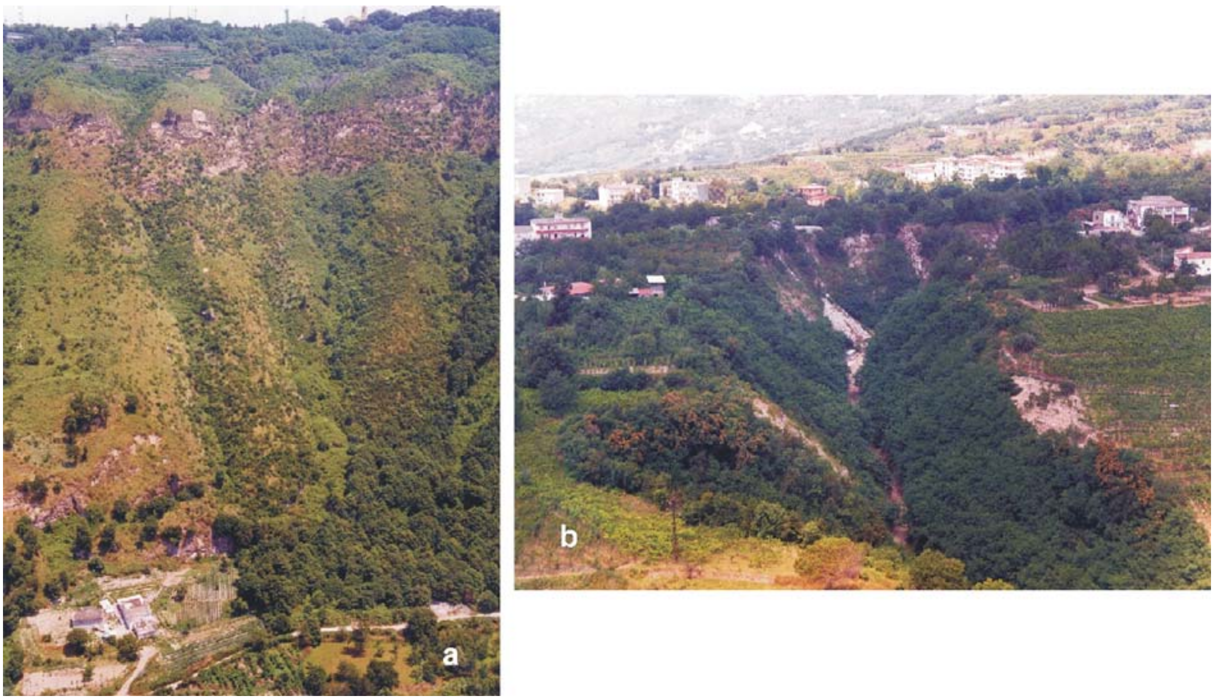

Fig. 7. Typical slope morphologies at the Camaldoli Hill: (a) frontal view of the southern sector, mostly planar, and with a limited development of slightly incised valleys; (b) example of deep valley in the northern sector, with steep walls and gradient. Note the proximity of houses and buildings to the upper reach of the drainage, and the illegal dumping of solid wastes.

case, these landforms are derived from the different response of exposed lithologies to erosion: zeolitized pyroclastics, Neapolitan Yellow Tuff, Soccavo Tuff, and Whitish Tuffs show vertical cliffs, whereas the gradient is much lower where loose deposits crop out. Among the tectonically-controlled cliffs, the most prominent is that between altitudes of 300 and 400 m a.s.l. This cliff took origin from the parallel retreat of a fault plane in the NYT, and has therefore to be dated after NYT emplacement, somewhere between 12,000 and 9500 years BP. Other scarps controlled by tectonics are those located at the footslope, and those which border the urban area of Pianura. They derive from the morphological evolution of fault planes belonging to the N–S system.

The western slope of the Camaldoli hill is morphologically subdivided in two distinct sectors: the southern sector, extending from Vallone S. Antonio to the south, and the northern sector, where the main slope direction curves from N–S to about NW–SE (Fig. 3).

The southern sector is mostly planar, with steep cliffs, mainly concentrated at the middle-upper slopes along a transverse profile (Fig. 7a); the valleys are of limited

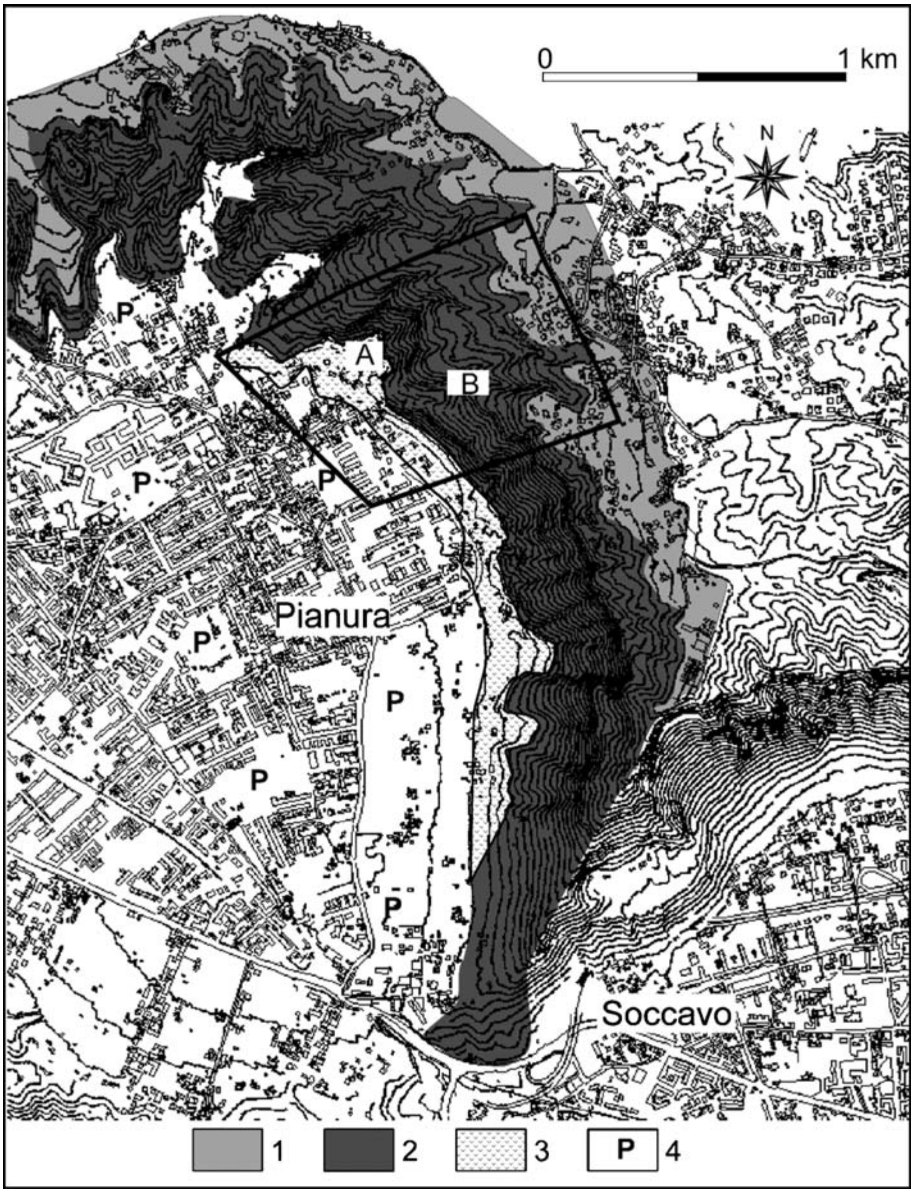

Fig. 8. Geomorphological zonation of the western slope of Camaldoli Hill. (1) Top highplain; (2) main slope; (3) footslope; (4) basal plain. Letter A marks the location of Piccola Lourdes, letter B that of Vallone S. Antonio. The inset refers to Fig. 9.

development, and are not deeply incised. Several slope instabilities affect this sector, mainly occurring as detachments of small to medium volumes of rocks, deposits (blocks up to 3–4 m^3) from which fill the gulches on the lower slope.

The northern sector, on the other hand, presents as a main morphological feature a number of deep canyons (Fig. 7b) which terminate just above the inhabited area of Pianura, often in correspondence with areas devoted to past quarrying activity. This activity caused major changes in the original morphology, and today the old quarries contain thick fillings of detritus derived from the extraction. The valleys are up to 800–900 m long, hierarchically organized up to the III order, and with gradients that often are above 40–60°, locally reaching vertical at the cliffs in the lithoid materials. The valleys are strongly controlled by tectonics, as evidenced by the linear path, the sharp bends, and the frequent steps, some up to several meters high, in the transverse profile.

In the northern sector, slope instability consists of several small to medium-size slides, and rock falls and topples at the vertical cliffs, which mostly correspond to old quarry walls, which are currently abandoned. In addition, deposits from landslides and erosion, mixed with solid wastes, are quite frequent within the deep and narrow valleys.

The transverse profile of the hill can be subdivided ideally into four different parts: the top highplain, the main slope, the footslope, and the basal plain. These sectors will be described in the following with the help of Fig. 8, which is an extract from the geomorphological map produced for the whole western slope of the Camaldoli hill. It covers the stretch of the slope that includes the passage from the northern, deeply-dissected sector to the southern planar sector.

The *top highplain* is a low inclined NW-dipping surface at elevations between 300 and 460 m a.s.l. As previously mentioned, this sector has been historically occupied by humans, which is also the origin of the diffuse environmental degradation and pollution, since solid wastes are illegally dumped into the valleys below, and liquid wastes are discharged along the main water lines and valleys.

The *main slope* is between the top highplain and the footslope, and presents the morphological differences previously outlined: the southern sector has mostly planar slopes with medium-high gradients (30–50°), locally reaching vertical; the northern sector, on the other hand, is more articulated, with several structurally-controlled and deep-incised valleys, which appear to be hierarchically organized.

In many cases solid wastes mixed with landslide deposits have been observed within the valleys. The presence of wastes at the thalweg of the valleys may cause, on the occasion of rainfall events, their remobilization and transport, so increasing the overall volume of materials transported downvalley; or, alternatively, they may create blockages, and cause the accumulation of further materials upvalley, with the likely consequence of sudden release of large amount of mixed deposits (Parise et al., 2004). At the mouth of some valleys, fan deposits have been recognized.

Land use changes are not limited to the top highplain, but occur also on the slope in the forms of terraces for agricultural practice, which are generally bordered by steep scarps on the valleyside. Some sectors of the western slope of the Camaldoli Hill are completely terraced, for example the ridge between Piccola Lourdes and Varchetta Valley (Fig. 9). Terraces are so widespread in some drainages that they are the main landform visible on the slopes. Pathways to enter the terraces and cultivate the fields frequently coincide with the old water ways and, on the occasion of rainstorms, work again as preferential lines for surficial runoff. Notwithstanding the widespread man-made terracing, remains of natural flat areas which can be correlated from one drainage to the other, are identifiable at different heights on the slopes.

Deepening of the drainage ways by linear erosion along the sectors located uphill from the main cliffs in the NYT has a double effect regarding slope instability: first, it favours the detachment of rock falls from the cliffs, and, second, it determines the development of hollows where the accumulation of debris, and their consequent removal by water, may occur. The hollows are in continuous transformation, and cause retreating of the watersheds, which, if not mitigated in some way, could induce instability and produce hazards to the infrastructures and houses at the border between the main slope and the top highplain.

In recent years, morphodynamics of the main slope seems to be also controlled by the effects of wild fires. A recent survey has shown that, from year 2000 to 2003, 152 wild fires, generally covering small areas (90% of the wild fires extended less than 10,000 m^2), involved the Camaldoli hill, burning more than 1,300,000 m^2 of land. As a consequence, landslides and, above all, sheet, rill and gully erosion were observed, with the main instability events registered in August 2001.

The *footslope* is the transition zone between the main slope and the basal plain where the inhabited area of Pianura is developing. This sector originated from the accumulation of debris coming from the main slope

Fig. 9. Geomorphological map of the area of Piccola Lourdes and Vallone S. Antonio. Explanation: (1) landslide scarp; (2) structurally-controlled torrent; (3) ridge; (4) saddle; (5) torrent; (6) fan; (7) step in the valley; (8) areal erosion; (9) fall; (10) slide; (11) flow; (12) small landslide; (13) tuff block; (14) flat area; (15) man-made scarp; (16) footpath; (17) path or incision with concentrated surface runoff; (18) intensely terraced area; (19) solid wastes. Elevations shown by cross and numbers.

which was deposited in the form of fans by erosional and gravitational processes in correspondence with the change in slope gradient. The fans were fed by different genetic processes, from water-laid transport to debris flows. Also in this area, the vicinity to the inhabited area caused heavy changes in the original morphology, and today it is not easy to recognize the original fans at the footslopes. A specific example of the modification by man exists at the terminal part of many valleys, where a dense network of artificial channels has been developed.

Many streams, in their path toward the inhabited area, loose their morphological form and have been heavily transformed, so that now the original stream has become a pathway or road to facilitate access to fields. Modifications of the natural surface runoff is quite common in many areas of the Campania region, and played a significant role in exacerbating the damage related to slope movements during the recent catastrophic landsliding events at Sarno, Quindici, and nearby towns in May 1998 (Parise et al., 2002).

The *basal plain* is the flat sector where the inhabited area of Pianura is located. It is morphologically similar to the top highplain, since it is a flat, heavily populated, sector. Uphill, the connection with the footslope is gradual, through a number of terraces. Only the portion of the plain which is closest to the footslope may be impacted by arrival of deposits on the occasion of landslide and flood events.

Eventually, it has again to be remarked the heavy role exerted by man on the recent morphology of the Camaldoli hill. Changes and modifications of the landscape have affected both the main slope and the low gradient sectors at its borders, and resulted in increasing the overall susceptibility of the slope to instability and erosion. In particular, the following man-made actions have produced the greatest impact in terms of instability on the Camaldoli slopes:

- ➢ removal of the vegetation over wide sectors of the slope, with consequent reduction of the natural protective action with regard to the process of areal erosion;
- ➢ modifications to the surface drainage network;
- ➢ discharge of liquid wastes in the valleys and streams, and the illegal presence of landfills of solid wastes within the valleys, or close to the main roads in the area;

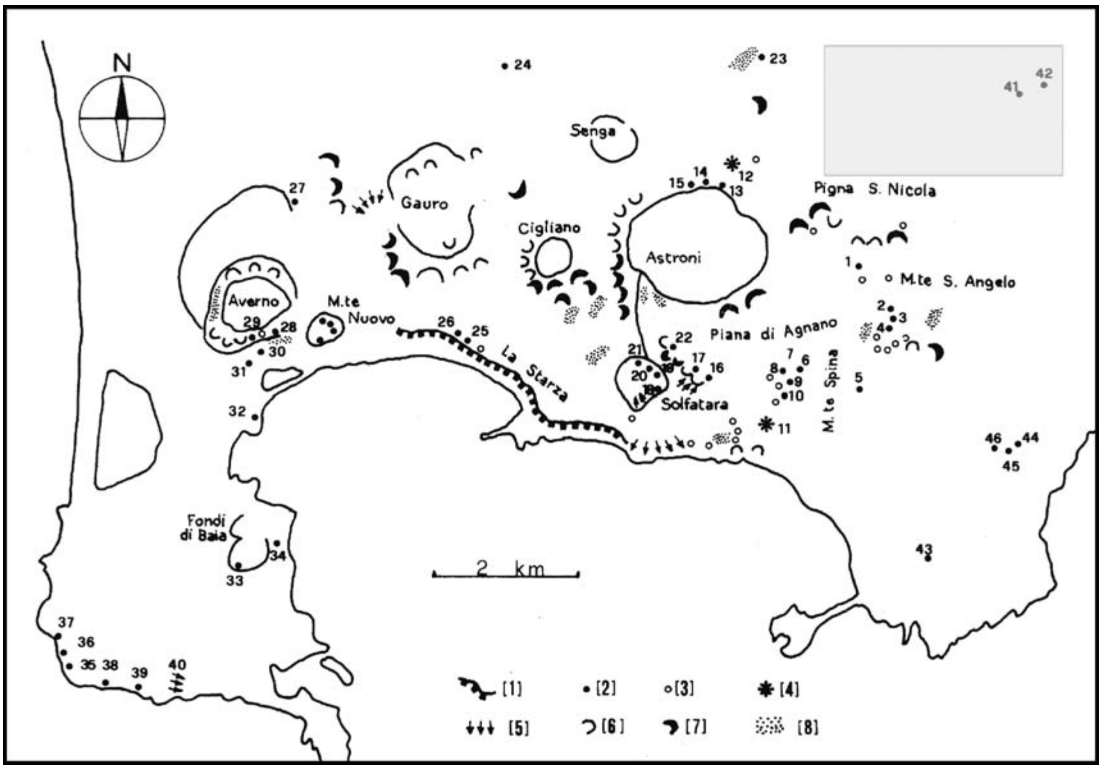

Fig. 10. Slope instability map of the Naples area (after Beneduce et al., 1988). Explanation: (1) terrace rim; (2) rapid earth flow; (3) debris slide; (4) earth slump; (5) rock fall; (6) areal erosion; (7) linear erosion; (8) shallow landslide. The inset refers to Camaldoli Hill.

- ➢ construction of pathways along streams, following the higher gradients and with no drainage works, aimed at collecting the surface runoff;
- ➢ lack of maintenance and cleaning of the valleys, including the artificial channels at their terminal part;
- ➢ wild fires.

4. Slope movements, erosion and weathering

The first studies on slope movements in the town of Naples date back to 1967, when a commission funded by the Municipality published a volume about the safety and stability conditions of underground Naples (Aa.Vv., 1967). In this study, slope instability was only marginally treated, because at that time the attention mostly focused on sinkholes related to underground cavities.

By the end of the 1980s, a specific study on slope instability in the Phlegraean area had been recorded (Beneduce et al., 1988): an overall number of 46 landslides were inventoried, about twenty of which were in the western area of Naples. Most of these were related to

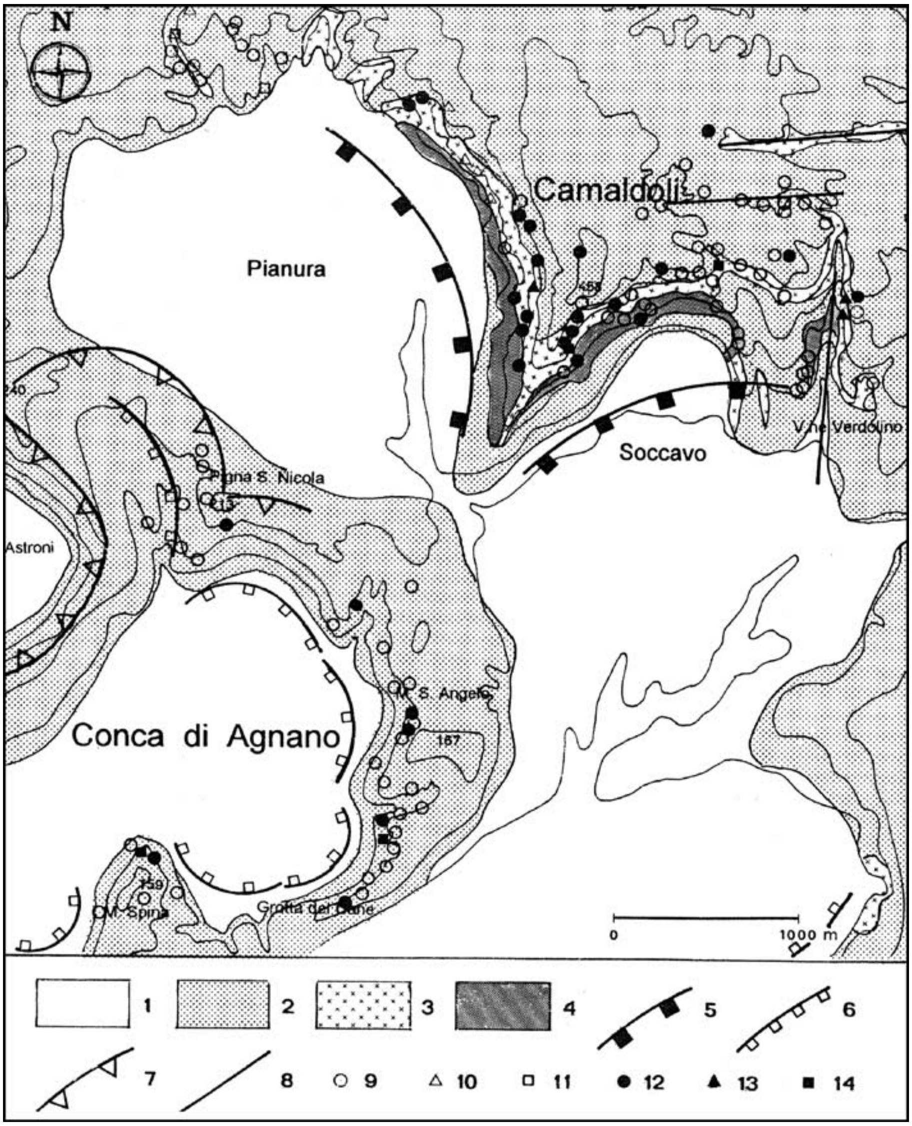

Fig. 11. Geological sketch and landslide inventory of the western urban area of Naples (after Calcaterra and Guarino, 1999a). Explanation: (1) reworked pyroclastics, alluvial deposits, fills; (2) loose pyroclastics younger than 15,000 years BP; (3) Neapolitan Yellow Tuff (about 15,000 years BP); (4) pyroclastics of the pre-NYT volcanic activity (Stratified Whitish Tuffs, Breccia Museo, Piperno, Torre Franco Tuffs); (5) rim of volcano-tectonic collapse (Phlegraean Caldera); (6) minor rim of volcano-tectonic collapse; (7) crater rim; (8) main fracture; (9) translational slide; (10) flow; (11) fall; (12) translational slide–flow; (13) fall–flow; (14) translational slide–fall. Contour interval 50 m.

the rainfall of the winter 1985–1986, and were located in the Agnano area (Fig. 10).

Pellegrino (1994), within the framework of an archival survey in the whole Province of Naples, and largely taking into considerations the data from Beneduce et al. (1988), reported over 120 landslides during the years 1986–1990. Calcaterra and Guarino (1999a,b) analysed the recent slope instability in the territory of Naples, with particular reference to 1996 and 1997 (Fig. 11). These authors remarked that most of the landslides were shallow slides, sometimes evolving to flows, and affected all the main hilly districts of Naples, and particularly the Camaldoli Hill. Eventually, Calcaterra et al. (2002) examined the historical landslide activity in Naples during the time span 1886–1996, and concluded that slope movements seemed to progressively affect areas where urban expansion developed in the last tens of years. In this framework, less than 10% of the landslides (out of the total 192) occur at the Camaldoli hill. These numbers point out the low incidence that mass movements had in the past in the morphogenesis of the Camaldoli hill, at least in regards to landslides large enough to be registered in the town chronicles.

The 1996–1997 rainfall and landslide events, on the other hand, pushed local authorities and the scientific community to study in detail the conditions of instability in the metropolitan area of Naples. During that winter, in fact, several episodes of slope instability involved the Neapolitan hillslopes, the most important of which occurred on January 10–11, 1997 (Calcaterra and Guarino, 1999a,b). On that occasion, from 9 to 10 January, about 110 mm of rainfall fell at Naples, with a peak hourly intensity of 10 mm and a mean intensity of 2.7 mm. The short-time event was preceded by a cumulated precipitation of about 1000 mm in 4 months, a value definitely higher than the mean annual precipitation. Consequently, more than 300 shallow landslides, mostly of the soil slide-debris flow type, involved essentially the loose pyroclastics younger than 15 ka, causing severe damages to man-made structures: about 40 of those mass movements were surveyed on the western slope of the Camaldoli hill.

Several geological and geomorphological studies were specifically funded and devoted to analysis of the stability conditions of slopes. In addition, the combination of field surveys and historical analysis resulted in the collection of information on numerous landslides, and the production of landslide inventory maps. An inventory of 380 mass movements was, for example, reconstructed for the period 1996–2001 by the Consortium between Universities of Naples and Salerno for Prevision and Prevention of Hydrogeological Risks (C.U.G.Ri., 1998–2001). Forty of these affected the Camaldoli area. Slope gradients at the detachment areas of these mass movements form an approximate Gaussian distribution, with values of gradient ranging from 27° to 65° (C.U.G.Ri., 1998–2001).

4.1. Slope movements

Detailed geomorphologic surveys were performed on purpose for this study to evaluate the susceptibility to landslides at the Camaldoli hill. Results from this analysis, cross-checked and integrated by interpretation of different sets of multi-year aerial photos, and by trench and drilling examinations, were quite in contrast with the outcomings of the previous studies on landslides in the area. The western slope of the Camaldoli Hill appeared in fact to be affected by widespread landsliding, and therefore has a medium to high susceptibility to mass movements.

The logistic difficulties in accessing many of the sites on the slope, and the presence of many vertical cliffs, have to be taken into account, because they likely contributed to an underestimation of the real number of landslides.

As shown in Fig. 12, in the overall sample of identified landslides, slides (mostly evolving to flows) are the most common type of landslide on Camaldoli Hill. If we consider, on the other hand, only the recent slope movements, falls present the highest frequency.

4.1.1. Falls and topples

Vertical or near vertical rock walls are frequently affected by detachment of blocks by fall or topple. Failure is controlled by the main discontinuity systems in the rock mass, which can be identified at the mesoscale, and determine the detachment of extremely variable volumes of rock. The spatial relationship between fracturing of the rock and geometry of the wall, and the development of weathering processes, seems to control the mechanism of movement. Even within the quarries, especially at the exposed walls, the effects of weathering on the rocks are clearly evident. However, the degree to which the variations in engineering properties are attributable to weathering, rather than original lithology is uncertain, and have to be carefully examined for each single case.

Joints are widespread and open, especially at the highest parts of the rock walls (Fig. 13). Nevertheless, their persistence and continuity through most of the rock wall (often down to the base) highlights the proneness to slope instability.

Inclined joints characterize the great majority of the examined cliffs, with at least three recognizable discontinuity systems per site. Due to the effects of weathering,

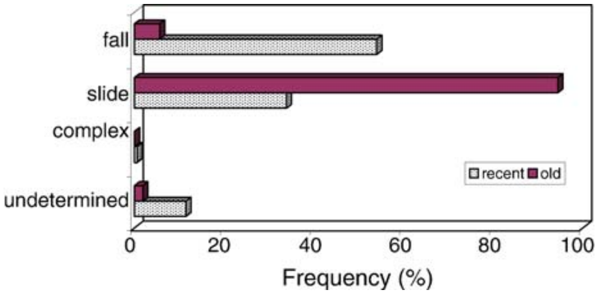

Fig. 12. Frequency distribution of landslide types (n=261).

the rock is more friable close to the discontinuities, and crumbles into small pieces. Discontinuities are often heavily stained and/or coated black; discoloration penetrating up to 3–4 cm along variable and sinuous fronts were also observed. Even though, based upon the above observations, the rock can be considered weathered to strongly weathered, it is not possible to quantify the degree to which the rock strength has been reduced by weathering.

In addition, as a further possible destabilizing factor, it is worth mentioning the presence of man-excavated caves at the base of many quarries: these caves, which were used in the past to store materials, are currently partly used for the production of fireworks. Due to height of the caves (several meters) and their overall length (in many cases over several tens of meters), these features may also play a role in enhancing slope instabilities. Unfortunately, due to lack of permission to access the caves, it was not possible to examine the likely connections between slope instability and cave presence and distribution.

Almost all the steepest cliffs, which are present at various heights along the slope at Camaldoli Hill, are affected by falls and topples. The closeness of anthropogenic infrastructures (including houses) to the cliffs, combined with the high susceptibility of the materials to failures, determines high vulnerability and high specific risk from these types of landslides. The most hazardous situations are:

a) all the quarry walls, with particular reference to those above Piccola Lourdes and the buildings in the Vallone Sant'Antonio;
b) some sectors located immediately downvalley of the main slope, e.g. those close to the road Vicinale dei Monti.

In these areas recent falls have been observed, such as that which involved CI materials on April 5, 2002, in the proximity of the church Piccola Lourdes (Fig. 14a). At this site, open fractures are still visible in the rock walls, which could thus evolve into detachment zones of future rockfalls.

The topography downslope from the detachment zone controls the evolution of the mass movement after the initial phase of fall or topple (Hungr et al., 1999; Wieczorek et al., 1999; Parise, 2002). In the case of slopes with more or less gradual gradient, detached blocks may move and travel for long distance. However, it is frequent that the displaced materials rest on the slope below the detachment zone, after a more or less short-range travel, as shown by the several blocks that are visible on the planar slope of the Camaldoli hill. Some,

Fig. 13. Rock wall in one of the many quarries located in the footslope area. Quarrying activity in the tuff was very active in the past. Abandoned quarries are today affected by frequent detachment and falling and toppling of rocks.

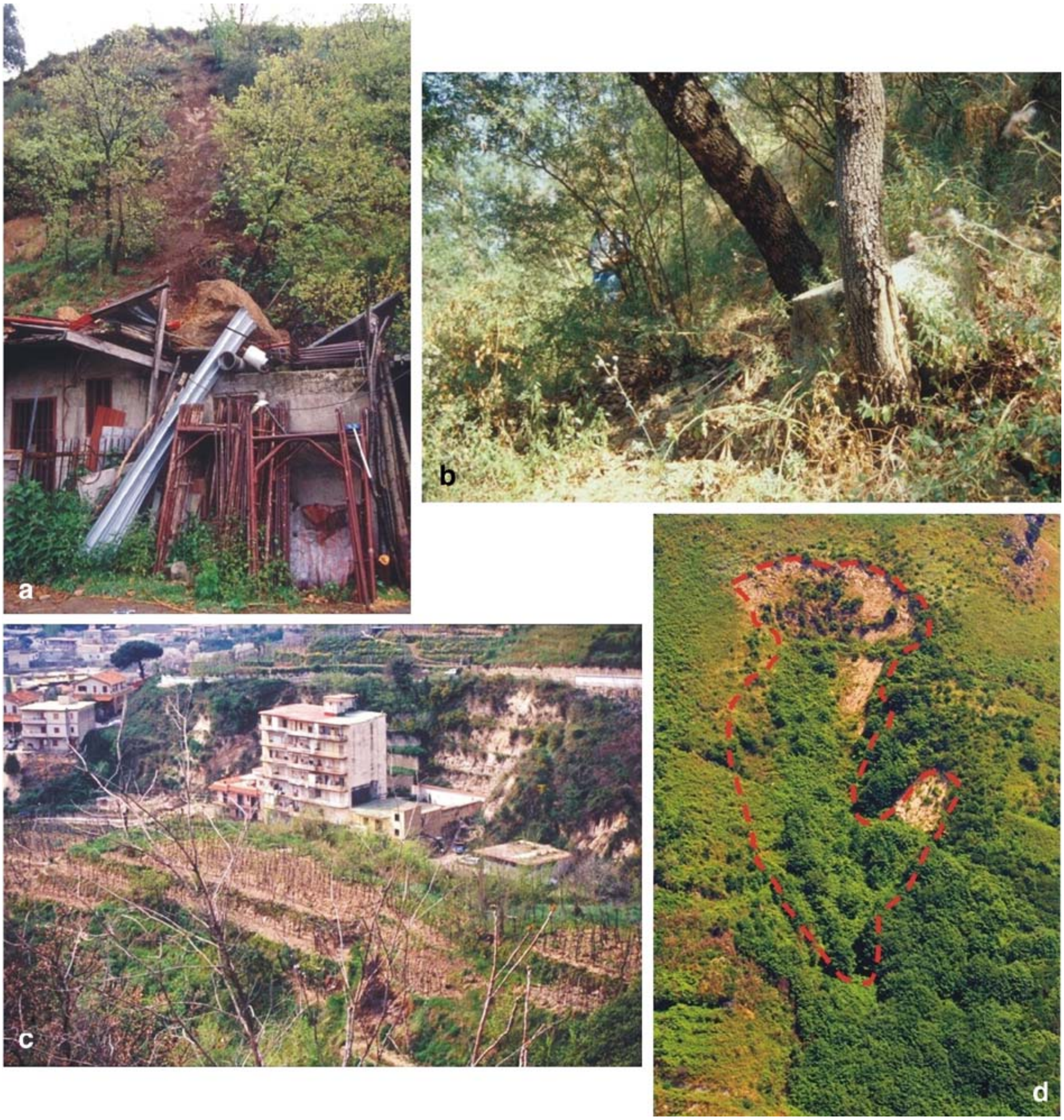

Fig. 14. Examples of slope movements at Camaldoli hill: (a) rockfall that occurred on April 5, 2002 near Piccola Lourdes; (b) block fallen from a tuff cliff and stopped by trees few tens of meters uphill from an inhabited area; (c) shallow soil slips in the Palmentiello drainage; (d) scar of a slide that occurred in January 1997, and reactivated in 2000 (photo taken in July 2000). Cases (a), (c) and (d) involved weathered pyroclastic deposits.

on the other hand, are able to acquire velocity and travel downslope, reaching the footslope area: there, the man-made terraces and the vegetation are important elements for mitigation of the risk, since they might stop the blocks or cause a decrease in their velocity (Fig. 14b).

In the northern sector of the study area, due to steep gradients, detached blocks are generally able to reach the valley bottoms, where they feed landslide debris which can be later remobilized on the occasion of floods and/or intense rainfall.

4.1.2. Slides–flows

Slides affect mostly the surficial pyroclastic cover, involving thickness on the order of 0.5–1 m. They are therefore shallow slides or soil slips (Campbell, 1975; Ellen, 1988), and involve the more weathered, generally loose, portions of surficial cover (Fig. 14c). Triggering is usually by rainfall; however, it must be mentioned that the negative effect from anthropogenic activities on the slopes, such as presence of mountain pathways, often occurs because of alteration of the original surface drainage. These pathways are not accompanied by any drainage or water channelling works, and further present unstable materials on the downvalley side, prone to be involved in slope movements. Even though soil slips have very high frequency in some sectors of the slope, generally, displaced materials travel for short distances, and stop along the slope, due to the small volumes involved, and the low relief. In many cases the detachment zone corresponds, or is located close to, pathways in the area.

Slides generally involve soils above the pyroclastic cover. Slide detachment areas have slope angle between 25° and 70° (Fig. 15). Landslide debris is generally loose, since materials in the source areas are frequently poorly consolidated. If the geomorphic configuration downhill from the source is suitable to transport of the detached material, this might cause partial blockage of the temporary drainage ways at the valley bottom, and deviations in the path of the water.

Both on the open slopes and within the valleys, slides did not evolve generally to rapid flows, as commonly occurs in other geological settings of the southern Apennines of Italy (e.g. Campania Apennines, where pyroclastics cover limestone bedrock; Calcaterra et al., 2000; Revellino et al., 2004). Such evolution, and the consequent high mobility, is therefore not typical for the Camaldoli hill, at least on the basis of the mass movements inventoried and examined in the years 1988–2000. On the other hand, the risk related to slides–flows depends upon their occurrence in areas close to the inhabited areas (the footslope and the borders of the top highplain).

A different type of evolution may be registered when the landslide debris, stored within the deep and narrow valleys, is mobilized on the occasion of heavy rainstorms in the forms of hyperconcentrated streamflow (Pierson and Costa, 1987). Large amount of debris, including landslide material, trees, and solid wastes, may be deposited at the mouth of the valleys. This mechanism was observed during the events of 15 September 2001 and 5 April 2002.

Even though several sectors of the western slope of the Camaldoli hill have been involved recently in wild fires, no specific relationships has been observed between presence of burned areas and development of mass movements, or, alternatively, an increase in erosion. However, it has to be remarked that the burned areas did not show evidence of very intense fires. Nevertheless, as recently pointed out by Cannon and Reneau (2000), and by Cannon et al. (2001), there is the possibility of an increase in erosion and landsliding in burned areas, which makes monitoring of these sectors necessary.

Eventually, as already observed in different geological settings (Jibson, 1989; Calcaterra et al., 2000), due to limited thickness of involved material in landsliding, the recognition of these mass movements may be very difficult because of the rapid growth of the vegetation which tends to cover the morphological evidence of the landslides (Fig. 14d). This problem might lead to an inaccurate assessment of the landslide hazard (Parise, 2001), underestimating the real susceptibility of the slope, and has to be properly considered when mapping slope movements in heavily vegetated areas.

4.2. Erosion and sedimentation

In addition to mass movements, processes of erosion have been observed in several areas of the Camaldoli hill. Erosion phenomena are both of areal and linear character, and consist mainly of the downslope transport of loose deposits which, on the occasion of the most intense rainfall, are mixed with blocks and solid wastes. Due to a lack of drainage works along pathways on the slopes, a relationship has been observed between erosional processes and the roads and pathways in the area.

With regard to erosional processes, the event of April 5, 2002, has to be mentioned when in approximately the same area affected by the aforementioned rock fall, the complete filling of a trench dug few days before was observed. The trench was located at the mouth of Piccola Lourdes valley. Filling consisted of sandy-loam deposits which were transported in pulses following several rainfall events between April 3 and 5. In detail, on April 4, after about half an hour of rainfall with average intensity of 6 mm/h, the trench was reached by flow of a mixture of water and mud: in about 15 min, an estimated volume of about 8 m^3 was deposited. At the end of the rainstorm, on April 5, about 11 m^3 of sediments had been deposited within the trench.

4.3. Weathering

Usually in volcanic terrains large volumes of volcaniclastic debris are produced and transported by processes, which are collectively called epiclastic processes, that include gravitational collapse or mass-wastage, chemical

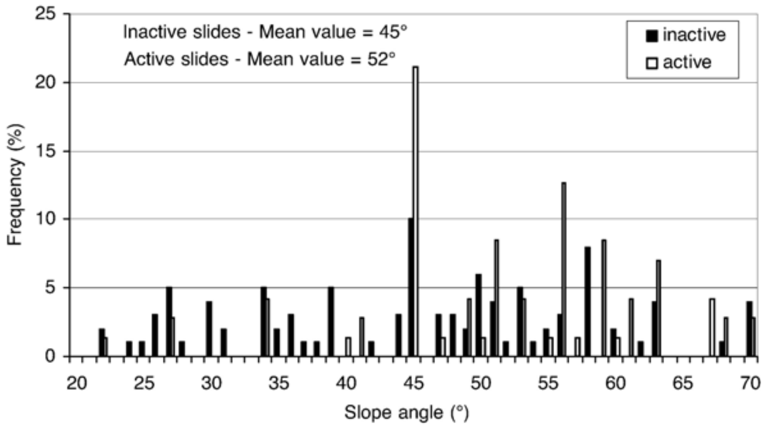

Fig. 15. Slope gradients in the detachment areas of slides/flows ($n=160$).

and physical weathering, and transport processes involving wind or water (Cas and Wright, 1987). Volcaniclastic materials may be affected by secondary mineralization processes, both during and after their deposition. These processes mainly affect the glass matrix of the deposits, as the amorphous fraction is much more reactive than the crystalline one, due to the different bond energy linking simple and complex ions into the structure (de' Gennaro et al., 1973). Therefore, as is the case of many Phlegraean volcanics, the amount of epigenetic minerals in pyroclastic deposits is proportional to the original glass fraction. The main agent of glass and crystals alteration is water, which causes in sequence hydration, hydrolysis and dissolution. According to the physical–chemical conditions of both deposits and circulating fluids, the alteration process can induce crystallization of tectosilicates (zeolites) or phyllosilicates (clay minerals). Zeolitization is the most diffuse process and affects most of the Phlegraean pyroclastic rocks (CI, NYT, Masseria del Monte and Verdolino Tuffs). Argillation (Keller, 1958), mainly produced by meteoric water-induced weathering, affects the upper portions of the exposed pyroclastic deposits. The high permeability of these rocks and the presence of a permeable bedrock, composed of fractured zeolitized tuffs, at the Camaldoli hill, favour leaching and crystallization of hydrous aluminosilicates. In the uppermost humified layers, allophane is the dominant mineral, with subordinate smectite and halloysite; this latter prevails in pumice lapilli beds. The soils of the Camaldoli hill (di Gennaro and Terribile, 1999) have been subdivided in: (a) soils with a moderately differentiated profile and andic properties, developed on loose-to-lithified ash and pumice fallout and density current deposits; (b) anthropogenic soils with a slightly differentiated profile; (c) subordinate, thin soils developed on lithified tuffs. These soils usually overlay complex sequences of vitric and allophanic soils, locally resumed by erosional processes, interlayered with slightly altered ash and pumice lapilli beds. Among the typical properties of the Phlegraean soils, characterized by variable andic properties, are low apparent density, high hydric retention, and high content of organic matter in the uppermost horizons.

The Camaldoli Hill is composed of a backbone of lithified (welded, sintered or zeolitized) rocks, mantled by loose pyroclastic, epiclastic and anthropogenic deposits, characterized by abrupt thickness and facies variations. Variable erosion, transport and deposition (or re-deposition) mechanisms contributed to rework these deposits and to distribute the detrital material along the slopes, and onto the plain, at variable distances from the footslope.

The loose and unconsolidated deposits largely cropping out at the western slope of the Camaldoli Hill are derived from weathering processes affecting the outermost portion of the volcanic sequence. Discriminating between in-situ weathered and reworked deposits along the slope is not an easy task, due to complexity, in both the lateral and vertical senses, of the sequence, and to superimposition of different processes of deposition. Nevertheless, field surveys and site investigations revealed the presence of various kinds of weathered or reworked products, outcropping at different positions along the slope.

In the uppermost reaches of the slope, a modern soil horizon is typically present, consisting of humified fine- to medium-grained ashes, brown to black in color, with dispersed fragments of pumice, lavas and tuffs. Its usual thickness is on the order of 0.2–0.5 m, locally increasing to 1.5–2.0 m due to agricultural practices. This top-soil horizon represents the product of the in-situ weathering and eventual pedogenization of the underlying loose

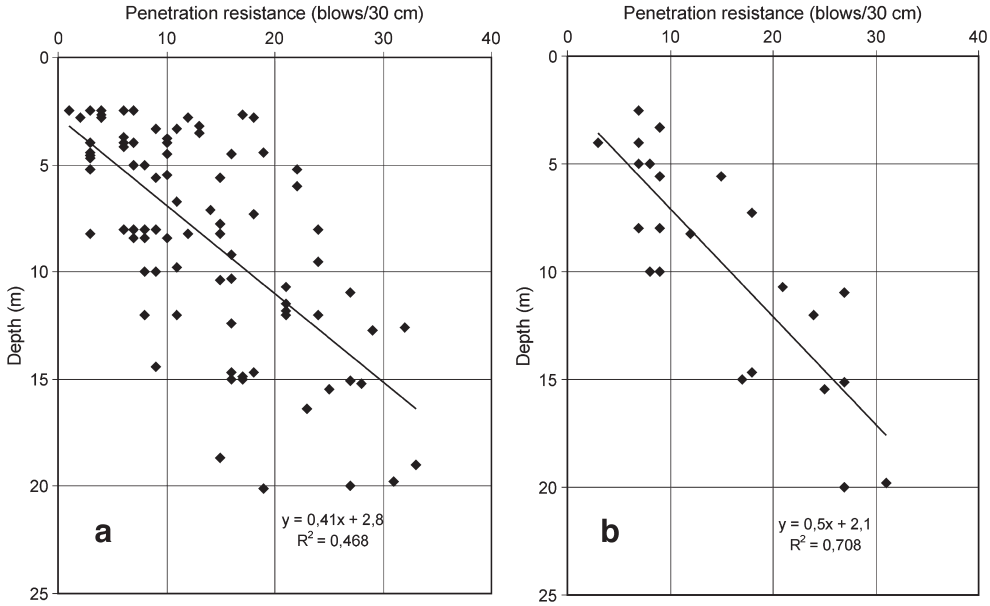

Fig. 16. Standard Penetration Tests of surficial deposits at Camaldoli hill: (a) overall plot; (b) tests performed at the upper reach of the main slope.

pyroclastics: it can be considered equivalent to either saprolite or residual soils of the typical weathered sequence in crystalline rocks (Geotechnical Control Office, 1984; Geological Society Engineering Group Working Party, 1995). The tendency of pyroclastic terrains to easily form pedogenised horizons is further evidenced by the frequent occurrence at variable stratigraphic height of more or less developed palaeosols, formed during very short time-intervals (Di Vito et al., 1999; Isaia et al., 2004).

In the middle-lowermost sectors of the hillside, an almost continuous cover of colluvial deposits mantle the oldest formations (from NYT to CI), fed by the erosional processes active on the slope. Colluvial deposits were drilled in several boreholes, showing a thickness between 2 and 8 m; these deposits are predominantly brown silts and medium- to fine-grained sands, sometimes humified, generally massive, with rounded pumice.

At the footslopes, especially at the mouths of gullies and valleys, various kinds of displaced terrains were recognized, being related to slope processes such as areal or linear water-laid deposition, debris flows, hyperconcentrated flows, rock falls. Their thickness is highly variable and may reach values up to 16 m.

Fills and man-made deposits prevail in the subsoil of the urban area, especially where quarrying activity has produced thick deposits of strongly heterogeneous materials, usually including blocks of tuff formations: these layers have been explored to a depth of 15 m from ground-surface.

Site investigations gave further emphasis to the presence and role of the weathered and reworked materials. Ninety-four Standard Penetration Tests (SPT) were executed during a campaign devoted to the geotechnical characterisation of Camaldoli Hill. The tests were located in some of the boreholes (Fig. 3) involving the surficial deposits (volcanics younger than 15 ka), down to maximum depth of 20 m. Overall, penetration resistance is not related to depth (Fig. 16a), clearly evidencing the pronounced structural and textural variability of loose deposits over the study area. However, if only the SPT data related to primary pyroclastic terrains and to their weathered products are considered, hence excluding displaced and man-made materials, a fair linear relationship is found (Fig. 16b). Moreover, in the first 5 m below the ground surface, less than 10 blows were constantly measured when performing SPTs, whilst the highest resistances were observed at a depth greater than 10 m.

5. Discussion

Present-day slope processes of Camaldoli Hill are strongly controlled by the widespread presence of weathered and reworked deposits on the slopes. In fact, several types of slope instabilities affect the surficial deposits which are derived from the underlying parent rocks. This observation caused us to pay greater attention to these deposits, aiming for a closer comprehension of their role in the overall hazard posed by the Camaldoli slopes to the downslope settlements. Within this scope a thickness map of the loose deposits was elaborated (Fig. 6): it shows that the deposits thicker than 5 m (class 4 and class 6) prevail near the top of the hill, along gently dipping slopes, and within the basal plain.

Distribution on the slope, and thickness of the loose deposits have then to be considered together with the data coming from the trenches and the subsurface explorations. The sedimentation rate calculated for the sequences exposed along the trench walls is reported in Table 2 with the interpreted time interval. A significant increase of the local sedimentation rate was detected at those sites where land reclamation and stream works or quarrying activity favoured sedimentation (Table 2). High sedimentation rate values have been calculated at the outlet of Piccola Lourdes, Palmentiello, Villa Tufo and Zoffritta valleys, and at Case Cannavino. The geological and geomorphological survey has shown that the studied area has been affected by intense erosional episodes between 15 and 5 ka BP. These episodes were likely related to climatic changes (lowering of the base level, different type of vegetation along the slopes) or to volcano-tectonic deformational events. The stratigraphic analysis of the cores drilled close to the depositional areas allowed us to better constrain the time of the beginning of the alluvial sedimentation. The time-interval of deposition of the alluvial sequences deposited above erosional unconformities cut into deposits of variable age, has been defined assuming the age of the youngest eroded marker bed as the age of beginning of the alluvial sedimentation. In Table 2 the results of the integrated analysis of trenches and core drillings within the depositional areas are reported. These areas (Fig. 17) have been defined on the basis of morphological, and both surface and subsurface geological features. All the available data have been used to evaluate the average thickness of the alluvial deposits in each depositional area. The average volume of solid material deposited per year, calculated on the basis of the total volume, fits the data obtained using the average sedimentation rate reasonably well. Starting from the assumptions made on the dynamics of the depositional systems and on the anthropogenic environmental conditioning, the sedimentation rate has been calculated considering sequences representing the depositional time-interval longer than 1.5 ka. This supports the hypothesis that the largest thickness values measured for short time-intervals are strongly influenced by local conditions of sedimentation. The general agreement between the specific degradation and the sedimentation rate values demonstrates that the processes of rapid erosion have been correctly evaluated, considering that the adopted estimation methodologies are different and mutually independent.

The overall geomorphic evidence, characterized by repeated erosional and landslide events, confirmed the need for remedial measures, devoted to protect the foothill district of Pianura. Such measures have been designed to protect against both kinds of phenomena, essentially adopting “passive” solutions.

6. Conclusions

This multidisciplinary study of the Camaldoli Hill allowed us to define the main lithostratigraphical and geomorphological aspects of the area, as well as the role played by slope instabilities in shaping the landscape. The present-day setting of the hill is derived from the interplay between depositional and deformational events. The former were represented by both constructive volcanic episodes and, subordinately, the remobilization of volcanic deposits due to gravitative processes, whilst the latter were produced by the volcano-tectonic activity during the last 40 ka. In regards to the stratigraphic sequence of the hill, two units representing remnants of tuff cones were identified in this study and named Masseria del Monte Tuff and Verdolino Tuff, respectively. The structural setting of the hill is characterized by the presence of two main

Table 2
Sedimentation rates in footslope areas (n.d. = not determined)

Deposition area	Extension of deposition area (m^2)	Mean thickness of alluvial and debris deposits (m)	Time interval of deposition (years)	Mean deposition rate (mm/year)	Total volume of sediments (m^3)	Volume of sediments/year, based on total volume (m^3/year)	Volume of sediments/year, based on mean deposition rate (m^3/year)
1	81,200	8.4	4800	1.6	683,700	142	130
2	56,000	6.7	4800	1.7	375,200	78	95
3	47,500	7.1	3800	1.8	337,400	70	86
4	36,400	11.6	3800	n.d.	422,240	111	n.d.
5	30,600	n.d.	3800	1.0	n.d.	n.d.	31
6	52,700	n.d.	3800	7.0	n.d.	n.d.	40

fault systems (N–S and N80E striking), which, along with a subordinate N40W set, are responsible for the severe jointing of the various formations and contribute to the susceptibility to fall and topple failures of the rock mass.

Following Parise et al. (2004), four geomorphological settings were recognized along with their specific processes. The top highplain is characterized by urban development which, having already deeply modified the original morphology, is also a causal factor for instabilities in the uppermost reaches of the slope. On the main slope, due to several predisposing factors (high slope angles; loose pyroclastics passing upwards to weathered and/or pedogenized cover; severely jointed weak rocks; anthropogenic action and related deposits) a variety of slope instabilities are present, among which four types prevail:

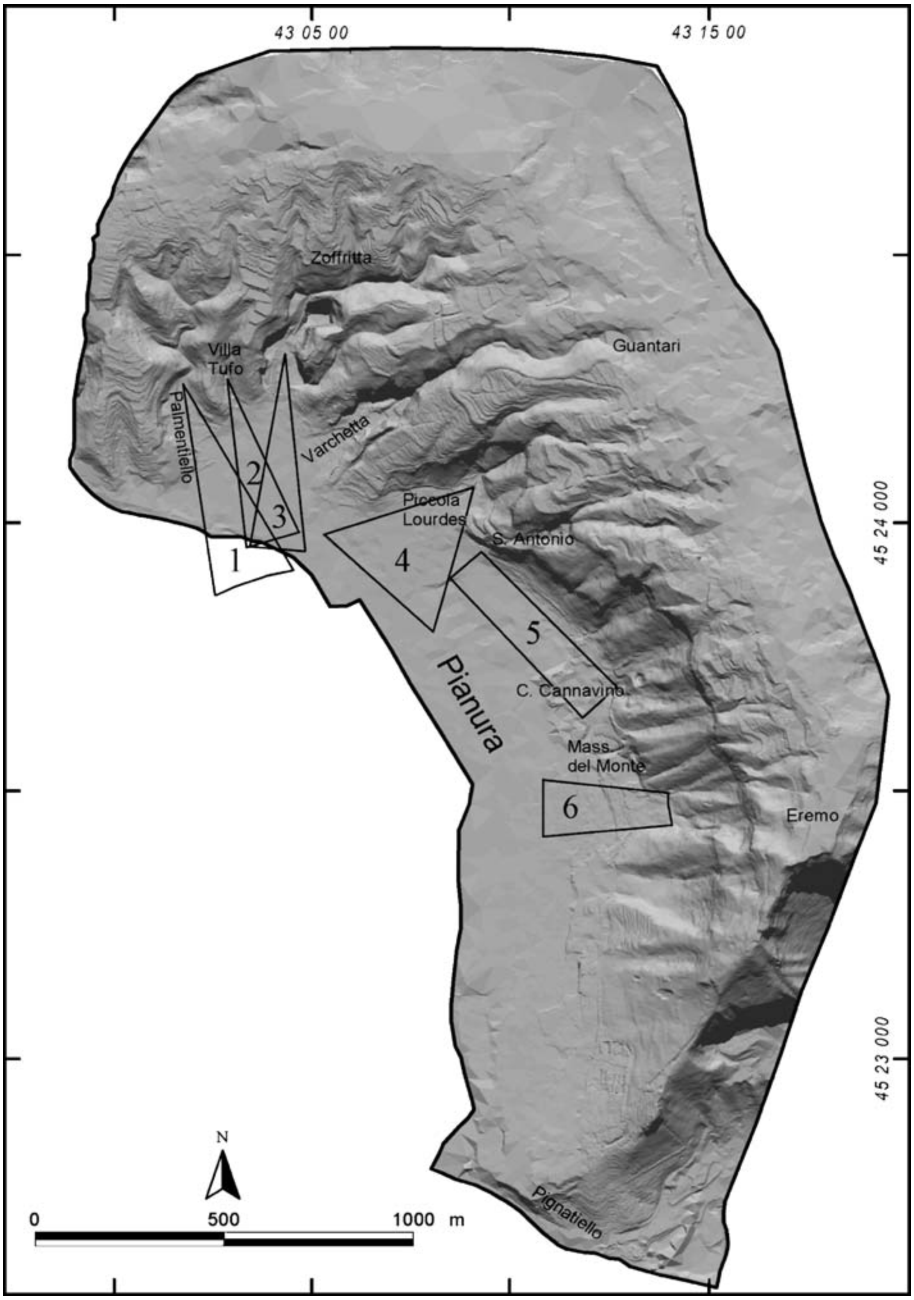

Fig. 17. Sectors of the plain in which analyses of sediments have been carried out, and sedimentation rates through time estimated. Numbers refer to deposition areas of Table 2.

a) falls and toppling failures from the vertical to high-angle cliffs carved in NYT;
b) small-scale slides involving the weathered and pedogenized loose cover which mantle all the outcropping formations. Occasionally, these slides are mobilized into fast moving debris flows;
c) "mixed" events, represented by initial slides of the b)-type, whose displaced materials are stored within the valleys, and later re-mobilized as hyperconcentrated flows, mud flows and debris flows;
d) areal and linear erosion, again involving the surficial, more weathered, portions of the pyroclastic sequence.

Materials from some of the above instabilities may reach the footslope where, at the outlet of the main valleys, mixed fans are present. Regarding the basal plain, the available data suggest that only the sectors closest to the footslope are exposed to invasion by materials derived from upslope processes.

In general terms, the western slope of the Camaldoli is susceptible to small-scale slope movements, whose potential of invasion into the footslope is in the order of a few hundreds of meters (Parise et al., 2004), hence showing a lower magnitude when compared to other sectors of the Campanian Apennines (Calcaterra et al., 2004). However, due to the widespread and uncontrolled urbanization, which in the last decades has spread over wide portions of the top highplain, at the footslope and on the basal plain, the overall landslide risk remains very high, as clearly stated by the official Risk maps produced by the local Basin Authority. A multi-stage remedial plan has been designed, the timing of which will depend on the availability of public funds. The first works will be devoted to facilitate the sediment deposition within some basins at the mouths of the main valleys. Eventually, slope works will be considered, aimed at reducing the susceptibility to slide failures and to mitigate the risk from potential invasion by rockfalls. In the first case, bio-engineering techniques will be extensively adopted, coupled with drainage works. In the second case, to reduce the risk of invasion related to rock failures, passive solutions as catch fences and barriers will be prevailingly employed to protect the settlements located at the footslope and in the basal plain.

Finally, this paper points out the high value of geomorphological mapping in dealing with engineering problems and geomorphic hazards. Especially in complex and heavily urbanized areas, the assessment of the landslide hazard, and adoption of measures to mitigate the related risk cannot proceed without a specific geomorphological approach, which is mandatory to any phase of engineering practice on the slope.

Acknowledgements

Jeffrey Coe (U.S. Geological Survey) and Cliff Ollier (University of Western Australia) are warmly thanked for their careful revision of the manuscript.

References

Aa. Vv., 1967. Il sottosuolo di Napoli. Municipality of Naples. 466 pp. (in Italian).

Barberi, F., Innocenti, F., Lirer, L., Munno, R., Pescatore, T., Santacroce, R., 1978. The Campanian Ignimbrite: a major prehistoric eruption in the Neapolitan Area (Italy). Bull. Volcanol. 41, 1–22.

Bartole, R., 1984. Tectonic structures of the Latian–Campanian shelf (Tyrrhenian sea). Boll. Oceanol. Teor. Appl. 2, 197–230.

Beneduce, P., D'Elia, G., Guida, M., 1988. Morfodinamica dei versanti dell'area flegrea (Campania): erosione in massa ed erosione lineare. Mem. Soc. Geol. Ital. 41, 949–961 (in Italian).

Calcaterra, D., Guarino, P.M., 1999a. Dinamica morfologica e fenomeni franosi recenti nell'area collinare napoletana (settore occidentale). Geol. Tec. Ambientale 2/99, 11–17 (in Italian).

Calcaterra, D., Guarino, P.M., 1999b. Fenomeni franosi recenti nell'area urbana napoletana: il settore centro-orientale. Proc. Congr. C.N.R.-Regione Emilia Romagna "Geologia delle grandi Aree Urbane", Bologna, 4–5 November 1997, pp. 257–261 (in Italian).

Calcaterra, D., Parise, M., Palma, B., Pelella, L., 2000. Multiple debris-flows in volcaniclastic materials mantling carbonate slopes. Proc. 2nd Int. Conf. on Debris-Flow Hazards Mitigation, Taipei (Taiwan), pp. 99–107.

Calcaterra, D., de Riso, R., Nave, A., Sgambati, D., 2002. The role of historical information in landslide hazard assessment of urban areas: the case of Naples (Italy). Proc. 1st European Conference on Landslides, Praha (Czech Rep.), pp. 29–135.

Calcaterra, D., de Riso, R., Evangelista, A., Nicotera, M.V., Santo, A., Scotto Di Santolo, A., 2004. Slope instabilities in the pyroclastic deposits of the carbonate Apennine and the Phlegraean district (Campania, Italy). Proc. Int. Workshop "Occurrence and Mechanisms of Flow-like Landslides in Natural Slopes and Earthfills", Sorrento, May 14–16, 2003, pp. 61–76.

Campbell, R.H., 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, Southern California. U.S. Geol. Surv. Prof. Pap. 851, 1–51.

Cannon, S.H., Reneau, S.L., 2000. Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico. Earth Surf. Processes Landf. 25, 1103–1121.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39, 171–188.

Cas, R.A.F., Wright, J.V., 1987. Volcanic Successions. Allen & Unwin, London. 487 pp.

Civetta, L., Orsi, G., Pappalardo, L., Fisher, R.V., Heiken, G.H., Ort, M., 1997. Geochemical zoning, mixing, eruptive dynamics and depositional processes — the Campanian Ignimbrite Campi Flegrei, Italy. J. Volcanol. Geotherm. Res. 75, 183–219.

Consortium between Universities of Naples and Salerno for Prevision and Prevention of Hydro-geological Risks (C.U.G.R.I.), 1998–2001. Reports of the research contract with the Municipality of Naples. Unpublished reports (in Italian).

D'Argenio, B., Pescatore, T.S., Scandone, P., 1973. Schema geologico dell'Appennino Meridionale. Quad. Acc. Naz. Lincei 183, 49–72 (in Italian).

Deino, A.L., Orsi, G., Piochi, M., de Vita, S., 2004. The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera — Italy) assessed by $^{40}Ar/^{39}Ar$ dating method. J. Volcanol. Geotherm. Res. 133, 157–170.
de' Gennaro, M., Franco, E., Stanzione, D., 1973. L'halloysite come prodotto di alterazione nelle vulcaniti campane e laziali. Atti Accad. Sci. Fis. Mat. In Napoli, Serie 3, 8, 1–35 (in Italian).
de Vita, S., Orsi, G., Civetta, L., Carandente, A., D'Antonio, M., Di Cesare, T., Di Vıto, M.A., Fisher, R.V., Isaia, R., Marotta, E., Ort, M., Pappalardo, L., Piochi, M., Southon, J., 1999. The Agnano-Monte Spina eruption (4.1 ka) in the resurgent, nested Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 91, 269–301.
De Vivo, B., Rolandi, G., Gans, P.B., Calvert, A., Bohrson, W.A., Spera, F.J., Belkin, A.E., 2001. New constraints on the pyroclastic eruption history of the Campanian volcanic plain (Italy). Mineral. Petrol. 73, 47–65.
di Gennaro, A., Terribile, F., 1999. I suoli della provincia di Napoli. Camera di Commercio, Industria, Artigianato e Agricoltura di Napoli. Ge. Pro. Ter., Napoli. 63 pp. (in Italian).
Di Vito, M.A., Lirer, L., Mastrolorenzo, G., Rolandi, G., 1987. The Monte Nuovo eruption (Campi Flegrei, Italy). Bull. Volcanol. 49, 608–615.
Di Vito, M.A., Isaia, R., Orsi, G., Southon, J., de Vita, S., D'Antonio, M., Pappalardo, L., Piochi, M., 1999. Volcanism and deformation since 12,000 years at the Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 91, 221–246.
Ellen, S.D., 1988. Description and mechanics of soil slip/debris flows in the storm. In: Ellen, S.D., Wieczorek, G.F. (Eds.), Landslides, Floods, and Marine Effects of the Storm of January 3–5, 1982, in the San Francisco Bay Region, California. U.S. Geol. Survey Prof. Paper, vol. 1434, pp. 63–112.
Fedele, F., Giaccio, B., Isaia, R., Orsi, G., 2003. The Campanian Ignimbrite eruption, Heinrich Event 4, and Palaeolithic change in Europe: a high-resolution investigation. In: Robok, A., Oppenheimer, C. (Eds.), Volcanism and Earth's Atmosphere. AGU Book, Geophysical Monograph, vol. 139, pp. 301–325.
Finetti, I., Morelli, C., 1974. Esplorazione sismica a riflessione dei Golfi di Napoli e Pozzuoli. Boll. Geofis. Teor. Appl. 16 (62/63), 175–222 (in Italian).
Fisher, R.V., Orsi, G., Ort, M., Heiken, G., 1993. Mobility of a Large-Volume Pyroclastic Flow — emplacement of the Campanian Ignimbrite, Italy. J. Volcanol. Geotherm. Res. 56, 205–220.
Geological Society Engineering Group Working Party, 1995. The description and classification of weathered rocks for engineering purposes. Q. J. Eng. Geol. 28, 207–242.
Geotechnical Control Office, 1984. Geotechnical manual for slopes. Geotechn. Control Office, Eng. Devel. Dept., Hong Kong, pp. 1–191.
Hungr, O., Evans, S.G., Hazzard, J., 1999. Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. Can. Geotech. J. 36, 224–238.
Ippolito, F., Ortolani, F., Russo, M., 1973. Struttura marginale tirrenica dell'Appennino Campano: reinterpretazione di dati di antiche ricerche di idrocarburi. Mem. Soc. Geol. Ital. 12, 227–250 (in Italian).
Isaia, R., D'Antonio, M., Dell'Erba, F., Di Vito, M.A., Orsi, G., 2004. The Astroni volcano: the only example of close eruptions within the same vent area in the recent history of the Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 133, 171–192.
Jibson, R.W., 1989. Debris flows in southern Puerto Rico. In: Schultz, A.P., Jibson, R.W. (Eds.), Landslide Processes of the Eastern United States and Puerto Rico. Geol. Soc. Am., Spec. Paper, vol. 236, pp. 29–55.
Keller, W.D., 1958. Argillation and direct bauxitization in terms of concentrations of hydrolyzing aluminium silicates. Am. Assoc. Pet. Geol. Bull. 42, 233–245.
Orsi, G., Gallo, G., Zanchi, A., 1991. Simple shearing block resurgence in caldera depressions. A Model from Pantelleria and Ischia. J. Volcanol. Geotherm. Res., vol. 47, pp. 1–11.
Orsi, G., D'Antonio, M., de Vita, S., Gallo, G., 1992. The Neapolitan Yellow Tuff, a large-magnitude trachytic phreatoplinian eruption: eruptive dynamics, magma withdrawal and caldera collapse. J. Volcanol. Geotherm. Res. 53, 275–287.
Orsi, G., de Vita, S., Di Vito, M., 1996. The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration. J. Volcanol. Geotherm. Res. 74, 179–214.
Orsi, G., Civetta, L., Del Gaudio, C., de Vita, S., Di Vito, M.A., Isaia, R., Petrazzuoli, S.M., Ricciardi, G., Ricco, C., 1999. Short-term ground deformations and seismicity in the resurgent Campi Flegrei caldera (Italy): an example of active block-resurgence in a densely populated area. J. Volcanol. Geotherm. Res. 91, 415–451.
Orsi, G., de Vita, S., Di Vito, M., Nave, R., Heiken, G., 2003. Facing volcanic and related hazards in the Neapolitan area. In: Heiken, G., Fakundiny, R., Sutter, J. (Eds.), Earth Sciences in the Cities: A Reader. Am. Geophys. Union, Spec. Publ. Series, vol. 56. American Geophysical Union, Washington, pp. 121–170.
Orsi, G., Di Vito, M.A., Isaia, R., 2004. Volcanic hazard assessment at the restless Campi Flegrei caldera. Bull. Volcanol. 66, 514–530.
Pappalardo, L., Civetta, L., D'Antonio, M., Deino, A., Di Vito, M.A., Orsi, G., Carandente, A., de Vita, S., Isaia, R., Piochi, M., 1999. Chemical and isotopical evolution of the Phlegraean magmatic system before the Campanian Ignimbrite (37 ka) and the Neapolitan Yellow Tuff (12 ka) eruptions. J. Volcanol. Geotherm. Res. 91, 141–166.
Parise, M., 2001. Landslide mapping techniques and their use in the assessment of the landslide hazard. J. Phys. Chem. Earth 26/9, 697–703.
Parise, M., 2002. Landslide hazard zonation of slopes susceptible to rock falls and topples. Nat. Hazards Earth Syst. Sci. 2, 37–49.
Parise, M., Calcaterra, D., Palma, B., 2002. Historical data analysis of landsliding and flooding events in Campania (Italy), as a tool for the assessment of the landslide hazard. Proc. 1st European Conference on Landslides, Praha (Czech Rep.), pp. 259–267.
Parise, M., Calcaterra, D., de Luca Tupputi Schinosa, F., Palma, B., 2004. Rockfall stability assessment at the western slope of the Camaldoli Hill (Naples, Italy). Proc. IX Int. Symp. on Landslides, Rio de Janeiro, vol. 1, pp. 257–263.
Pellegrino, A., 1994. I fenomeni franosi nell'area metropolitana napoletana. Proc. Conv. "Rischi naturali ed impatto antropico nell'area metropolitana napoletana". Acta Neapol. 18, 237–256 (in Italian).
Pierson, T.C., Costa, J.E., 1987. A rheologic classification of subaerial sediment–water flows. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches: Process, Recognition, and Mitigation. Geol. Soc. Am., Reviews in Eng. Geol., vol. 7, pp. 1–12.
Revellino, P., Hungr, O., Guadagno, F.M., Evans, S.G., 2004. Velocity and runout simulation of destructive debris flows and debris avalanches in pyroclastic deposits, Campania region, Italy. Environ. Geol. 45, 295–311.
Rittmann, A., 1950. Sintesi geologica dei Campi Flegrei. Boll. Soc. Geol. Ital. 69, 117–177 (in Italian).
Wieczorek, G.F., Morrissey, M.M., Iovine, G., Godt, J., 1999. Rock-fall potential in the Yosemite Valley, California. U.S. Geol. Survey Open-File Rep., vol. 99-578. 7 pp.