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Landslides, volcanism and volcano-tectonics: the fragility of the Neapolitan territory

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Landslides, volcanism and volcano-tectonics: the fragility of the Neapolitan territory

Post meeting Field Trip of Cities on Volcanoes 10, Napoli/Italy September 2-7-2018

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Abstract

Small landslides to large debris flows and debris avalanches affected the Neapolitan territory surrounding the active volcanoes of the area: Vesuvius, Campi Flegrei and Ischia. Their variable intensity explosive eruptions produced significant quantities of loose pyroclastic material on the slopes of the volcanoes and of the surrounding reliefs. Remobilization processes of this material occurred during and soon after large explosive eruptions, although their intensity and frequency decreased during inter-eruptive periods. The intensity of these processes varies with the different eruptions and is strongly dependent on availability of fine ash in proximal and distal areas. The areas involved varies from hundreds to millions square meters. The syn-eruptive debris flows of the Vesuvius 472 AD eruption are described in detail. Huge ground uplift of the central part of the Ischia resurgent caldera generated debris/rock avalanches, which likely caused tsunamis. Archaeological sites affected by syn-eruptive debris flows have been selected to show the effects of their deposition. Hydraulic risk and risk mitigation actions, emergency management and preparedness measures will be discussed in one of the areas mostly affected by recent debris flows. At Ischia the characteristics of debris/rock avalanches and lahars related to the resurgence and to the reactivation of volcanism will be discussed.

Keywords: *volcanism, landslides, debris flows, debris avalanches, hydraulic risk, risk mitigation.*

Program summary

This field trip will focus on syn-eruptive and post-eruptive debris flows occurred in the Neapolitan area. Eruptions and ground deformations of the three active volcanoes of the area, Vesuvius, Campi Flegrei and Ischia, produced large remobilization processes of pyroclastic deposits, which affected wide sectors of the areas surrounding the volcanoes. The scale of these phenomena is variable from small landslides to large debris flows and debris avalanches, and the extent of the areas involved varies from hundreds to millions square meters. Large debris flows occurred during and soon after large explosive eruptions, although their intensity and frequency decreased during inter-eruptive periods. Huge ground uplift of the central part of the Ischia resurgent caldera generated debris/rock avalanches, which likely caused tsunamis.

Participants will enjoy the visit of spectacular archaeological sites affected by syn-eruptive debris flows, related to a historical eruption of Vesuvius (Pollena, 472 AD) in both proximal and distal areas. At the mouth of an

Apennine valley (Sarno), participants will have the opportunity to visit a site with syn-eruptive/post-eruptive debris flows and discuss their timing, distribution, impact and risk mitigation actions. At Sarno a C.O.C. (Municipal operative center) will be visited with the help of local authorities and themes such as hydraulic risk, emergency management, preparedness measures and response actions will be discussed.
The trip also includes a day dedicated to Ischia, aimed at discussing the characteristics of debris/rock avalanches and lahars deposits related to the Mt. Epomeo resurgence, slow ground deformations preceding debris avalanche generation, and impact of eruptions on human settlements of variable age.
During the field trip, pyroclastic sequences emplaced by Vesuvius, Campi Flegrei and Ischia, locally intercalated with remains of historic and prehistoric human settlements, will be observed and discussed.
The main aim of the trip is to explore the impact of phenomena strictly related to eruptions on territory and on human settlements, and the risk mitigation actions adopted in this fragile context.

List of stops

1st day

Stop 1.1: Villa di Augusto at Somma Vesuviana (451482 E, 4525137 N)
Significance: syneruptive debris flows related to the Pollena eruption and their impact on Roman structures and buildings. Discussion points: timing of debris flows occurrence and their relationships with the primary deposits, impact on buildings.

Stop 1.2: Nola Amphitheater Laterizio (459691 E, 4530851 N)
Significance: historical debris flows in the Campanian Plain. Discussion points: impact of debris flows on distal areas, landscape modifications, timing of phenomena.

Stop 1.3: Sarno (467440 E, 4519874 N)
Significance: syn-eruptive debris flows related to the 1631 AD eruption, and their relationships with the primary deposits along the Apennine valleys. Recent debris flows (May 1998) and their impact. Discussion points: syn-eruptive/post-eruptive debris flows, timing, distribution, impact, risk mitigation actions.

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Stop 1.4: Nocera Inferiore – Monte Vescovado debris avalanche (470474 E, 4508911 N)
Significance: recent landslide (March 2005) – Vescovado locality. Discussion points: post-eruptive debris avalanches, origin and relationships with the primary pyroclastic deposits.

2st day
Stop 2.1: Mugnano del Cardinale (472416 E, 4528203 N)
Significance: pyroclastic sequences of the Vesuvius eruptions along the Apennine slopes. Discussion points: emplacement mechanism, internal sequence, grain size and relationships with debris flows.

Stop 2.2: Quindici (470505 E, 4523034 N)
Significance and discussion point: the geomorphological features of recent debris flows (May 1998).

Stop 2.3: Piani di Prata (470512 E, 4520194 N)
Significance: source areas of recent landslides and the typical highland landscape of the carbonate Apennines. Discussion points: present and past phenomena and efficiency of the risk mitigation actions.

Stop 2.4: Sarno C.O.C. (467987 E, 4518205 N)
Significance: visit to a Municipal Operative Center. Discussion points: hydraulic risk, emergency management, preparedness measures/response actions.

3st day
Stop 3.1: Monte Nuovo, Forio, Ischia (405230 E, 4508952 N)
Significance: Monte Nuovo, deep seated rock mass deformation due to Mass Rock Creep (MRC) as a possible stage preceding rock avalanche generation. Discussion points: relationships between volcanism and related phenomena (timing, impact, characteristics).

Stop 3.2: Forio (405577 E, 4507764 N)
Significance: the deposits of debris/rock avalanches and lahars related to the Mt. Epomeo resurgence. Discussion points: relationships between volcanism and related phenomena (timing, impact, characteristics).

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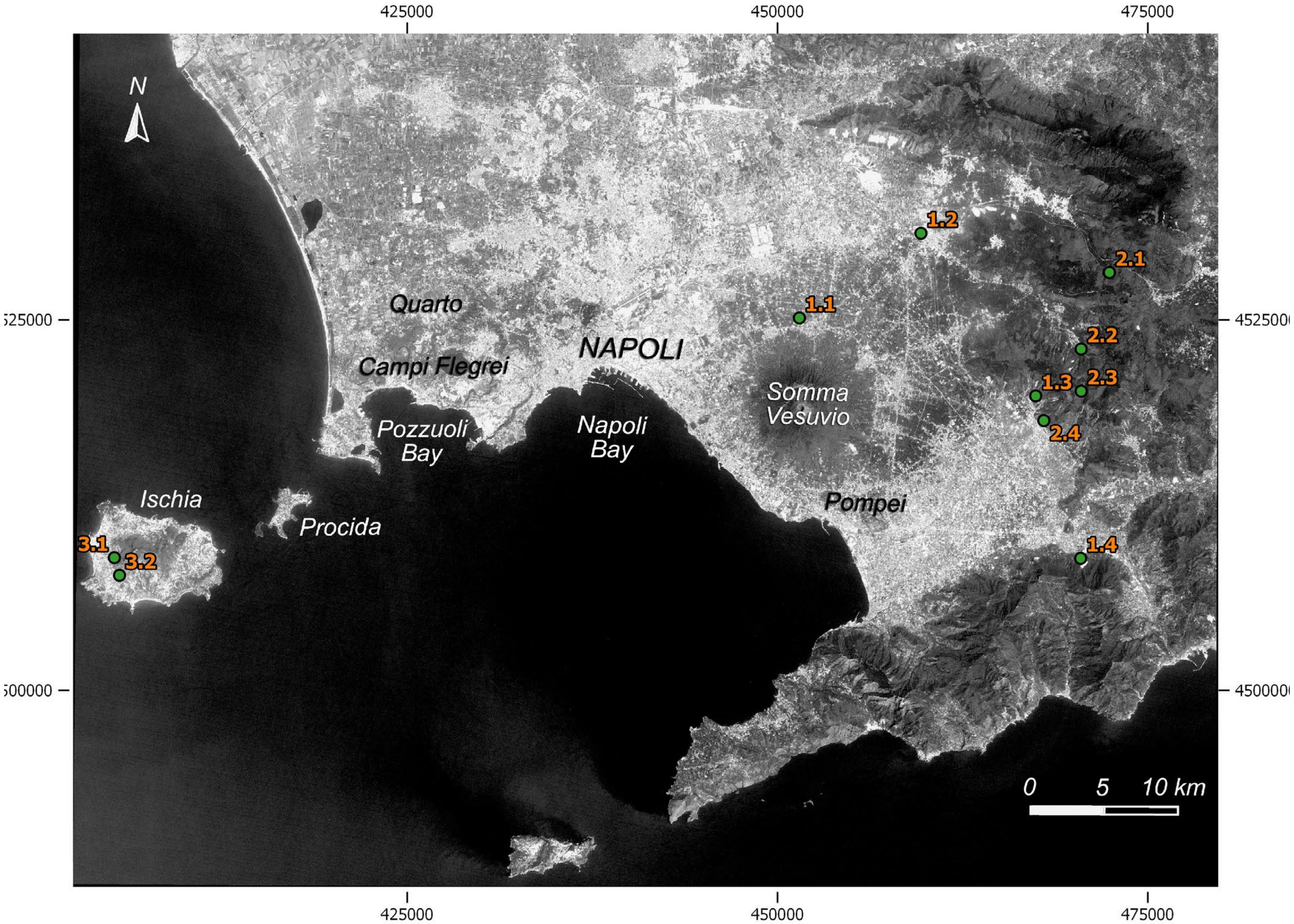

Fig. 1 - Stops of the field trip. 1.1: Villa di Augusto; 1.2: Amphitheater Laterizio; 1.3: Sarno; 1.4: Nocera Inferiore; 2.1: Mugnano del Cardinale; 2.2: Quindici; 2.3: Piani di Prata; 2.4: Sarno C.O.C.; 3.1: Monte Nuovo (Ischia); 3.2: Forio.

Safety

Hospitals:
Ospedale Santa Maria della Pietà, Via delle Repubbliche, 7, 80035 Nola (NA). 081/822311
Ospedale Maresca, via Montedoro, 80059 Torre del Greco (NA). Tel. 081/8490111
Ospedale Rizzoli, via Fundera, 2, 80076 Lacco Ameno (NA). Tel. 081/5079111

Accommodation:
Hotel Marad, via Benedetto Croce, 20, 80059 Torre del Greco (NA). Tel. 081/8492168
Grand Hotel Punta Molino, Lungomare Cristoforo Colombo, 23, 80070 Ischia (NA).
Tel. 081/991544

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1. The Campania landscape

Campania is a region distinguished by a marked geological and geomorphological difference between the eastern part, largely mountainous or hilly, and the western side, which is mainly flat. The eastern region includes the Apennine chain; the western region, which occupies the coastal strip, is mostly made up of two flat areas, the Campanian Plain and the Sele Plain, separated by the Sorrento Peninsula (Fig. 1). The contrast within this sector is accentuated by the presence of a series of Quaternary volcanic edifices along the Tyrrhenian part of the Campanian Plain.

The Plain is a NW–SE elongated graben filled with Plio-Quaternary sedimentary and volcanic deposits (Santangelo et al., 2017 and references therein). Its development is related to the eastward migration of the Apennine thrust belt front and to the southeastward migration of extension due to the opening of the Tyrrhenian basin (Vitale and Ciarcia, 2018 and references therein). Apennines are made up of Meso-Cenozoic carbonates and middle Miocene-Pliocene siliciclastic deposits and border the northern, eastern, and southern margins of the Campanian Plain (e.g. Vitale and Ciarcia, 2013) (Fig. 2).

Four main volcanoes are present in the Neapolitan area: Somma-Vesuvius, Campi Flegrei, Ischia, and Procida (Fig. 1). The onset of volcanic activity occurred about 300-400 ka in the Vesuvian area (Principe et al., 1987; Brocchini et al., 2001), >150 ka in the Ischia Island (Poli et al., 1987), >60 ka in the Campi Flegrei area (Pappalardo et al., 1999), and >70 ka at Procida (Rosi et al., 1988).

Only three of these are still active today: Somma-Vesuvius, the Campi Flegrei caldera and the Isle of Ischia (Orsi et al., 2003; Santacroce et al., 2003; de Vita et al., 2010).

These volcanoes have produced numerous explosive and effusive eruptions. The events of greatest intensity affecting the continental portion of Campania are associated with the Somma-Vesuvius and Campi Flegrei caldera activity: the former in the last 10 kyr produced the Plinian eruptions known as pomici di Mercato (8.8 ka; Santacroce et al. 2008), pomici di Avellino (3.95 ka; Passariello et al. 2009; Sulpizio et al., 2010b; Sevink et al., 2011) and pomici di Pompei (79 AD, Sigurdsson et al., 1985), and the latter the pomici principali (10.3 ka, Di Vito et al., 1999) and Agnano-Monte Spina eruptions (4.55 ka; de Vita et al., 1999; Smith et al., 2011).

Comparative archaeological and volcanological studies conducted in Campania show that the effects of the Vesuvius and Campi Flegrei eruptions have strongly influenced the growth and decline of many human settlements over the millennia. The long history of interaction between humans and volcanoes is recorded

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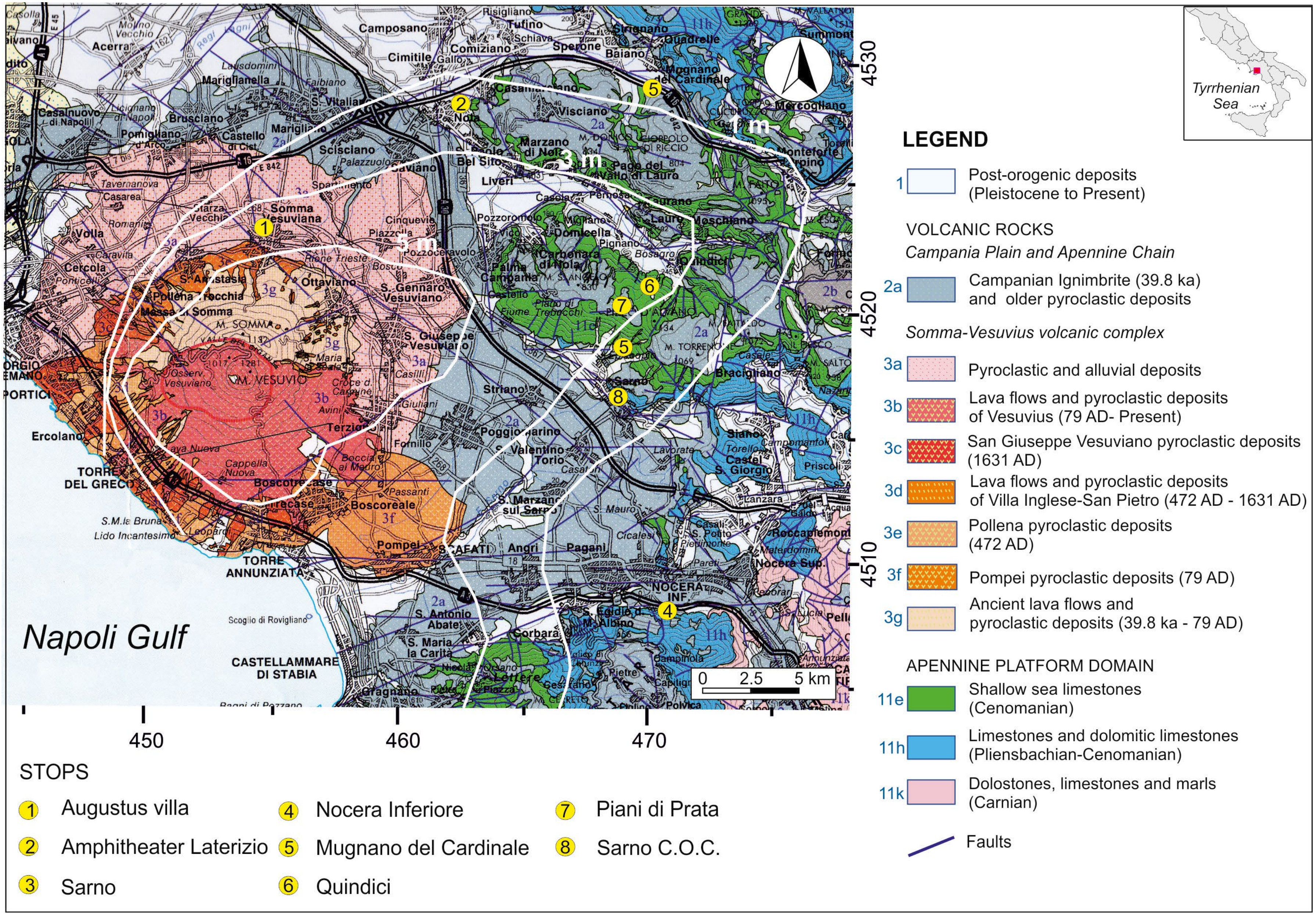

Fig. 2 - Location of the proposed on-land stops on the 1:250.000 Geological Map of Campania modified after Ciarcia and Vitale (2018). The white contours, redrawn from Lirer et al. (2001), are the isopaches summing the thicknesses of all the pyroclastic fall deposits emplaced by Somma-Vesuvius in the last 10 kyrs.

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in detail in the stratigraphy in areas both close to the volcanoes and farther away, up to several tens of kilometres east and north of the eruption vents (Talamo, 1999; Marzocchella, 2000; Albore Livadie et al., 2005; Talamo and Ruggini, 2005; Di Vito et al., 2009; Laforgia et al., 2009). Volcanic eruptions and associated phenomena have often caused interruptions in the occupation of these areas, but have also contributed to the exceptional fertility of the soils, which allowed intense agricultural activity. Moreover, the accumulation of significant quantities of loose pyroclastic material on the slopes of the hills surrounding the plain (Fig. 2) has resulted in repeated lahar generation and flooding episodes, causing the development of marshlands and the build-up of thick detrital layers (Di Vito et al., 1998; Zanchetta et al. 2004a, b; Sulpizio et al., 2006; Di Vito et al., 2013; 2018).
During the periods of quiescence between the various eruptions, generally longer than the span of a generation, humans have found it advantageous to establish settlements in this area, not only for the high fertility of the soil and favourable climatic conditions, but also due to the geographical location, which favoured trade with neighbouring territories.

1.1 Campi Flegrei

The Campi Flegrei caldera, partially submerged beneath the Gulf of Pozzuoli, is a resurgent nested structure formed during two major collapses related to high-volume eruptions. The first occurred during the "Campanian Ignimbrite" eruption (40 ka; Giaccio et al., 2017 and references therein) and affected a larger area with respect to the second one determined by the "Neapolitan Yellow Tuff" (14.9 ka; Deino et al., 2004).
The erupted products, distributed over a wide area, have a total volume ≥400 km^3 (DRE) and are commonly tuffs; these were mostly deposited during the two caldera-forming eruptions, although the majority of eruptions produced less than 1.5 km^3 of pyroclastic deposits from monogenetic centres (e.g., Piochi et al., 2005a; Di Renzo et al., 2011; Smith et al., 2011). The juvenile components of these deposits are glass shards, pumice and scoria fragments, while the lithic portion includes tuff, lava and hydrothermal/ hornfelsed altered clasts, and fragments from the sedimentary basement. Effusive eruptions sporadically formed lava domes.
The "Campanian Ignimbrite" eruption and caldera collapse was the largest magnitude explosive event of the Mediterranean area over the past 200 kyrs, profoundly influencing the present local geological setting. The produced volcanic succession includes a basal Plinian fallout and mostly welded ash and pumice

flow deposits derived from several pyroclastic density currents generated through multiple feeding fractures, affecting an area of about 7,000 km^2 (Piochi et al., 2005a).

After the "Neapolitan Yellow Tuff" eruption and related caldera collapse that occurred within the 40 ka-caldera, at least 70 eruptions, took place in three epochs of intense activity (15.0÷9.5, 8.6÷8.2 and 4.8÷3.8 ka) and followed one to another at mean time intervals of a few tens of years. The last event was in 1538 AD, after about 3.0 ka of quiescence, and formed the Mt. Nuovo tuff cone (Di Vito et al., 1987; Piochi et al., 2005b; Di Vito et al., 2016). 64 of these eruptions were phreatomagmatic to magmatic explosive events, and 76% of these eruptions occurred from vents active in the central-eastern sector of the caldera (Mormone et al., 2011). Fallout deposits of the I epoch were distributed manly toward the north-eastern sector of the caldera and the Camaldoli hill, 15 km from the caldera centre (Fig. 3). Only fallout beds of the pomici principali tephra are widely distributed and are 20 cm thick along the western margin of the Apennines, at about 50 km from the vent. Pyroclastic currents travelled within the caldera floor and reached the Campanian Plain. The eruptions of the II epoch were all low-magnitude events. Fallout deposits covered only the caldera and its immediate surroundings, while most of the pyroclastic currents deposited their load within the caldera lowland. The fallout deposits of the III epoch and of the Mt. Nuovo eruption covered the caldera floor and its surroundings (Fig. 3). Only beds of the Agnano-Monte Spina tephra, the largest sub-Plinian post-caldera

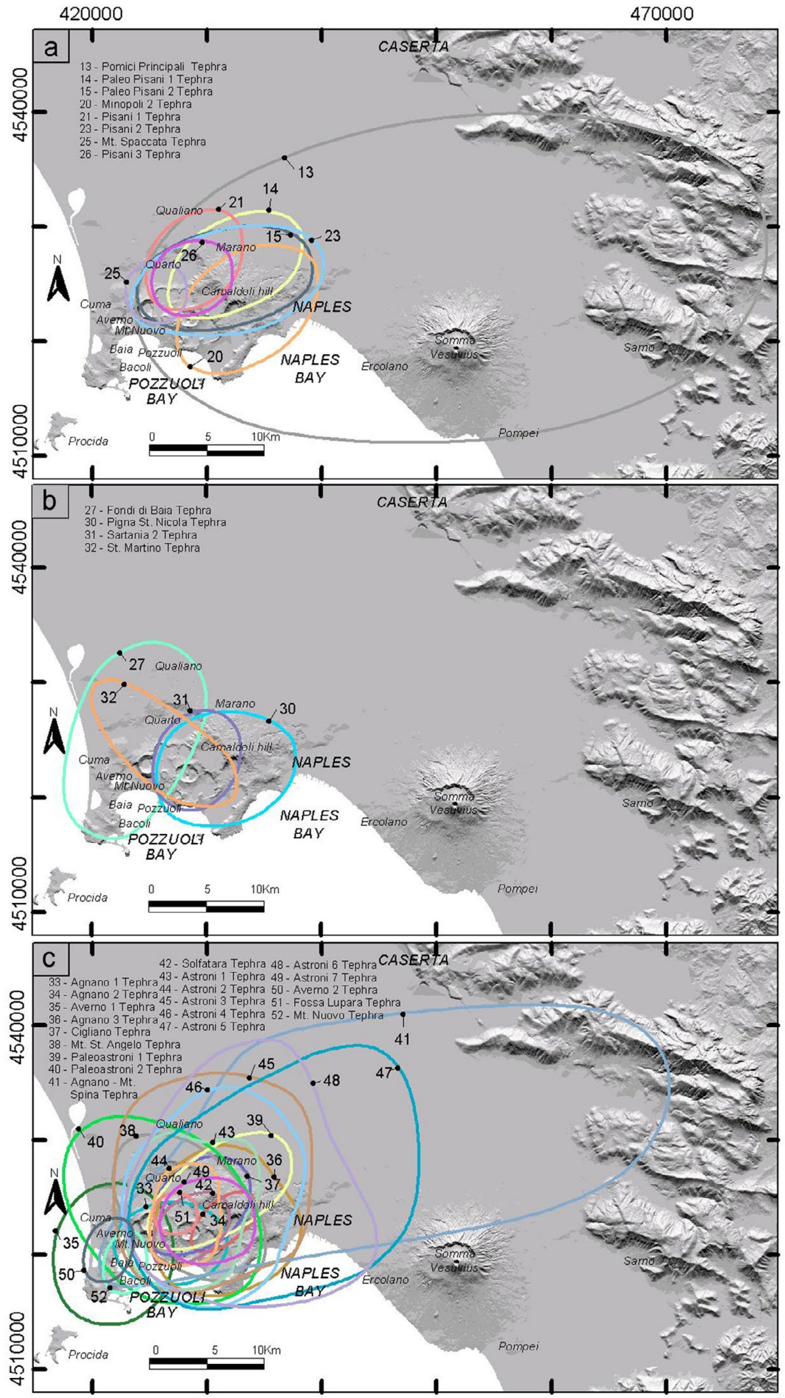

Fig. 3 - Distribution of the pyroclastic fallout deposits of the past 15 kyrs at the Campi Flegrei caldera (from Orsi et al., 2004). a, b and c: fallout beds thicker than 10 cm of the I, II and III epoch, respectively.

event, covered a large area up to the Apennines. Pyroclastic currents travelled across the caldera floor and subordinately over the northern slopes of the Camaldoli hill (de Vita et al., 1999; Orsi et al., 2004).
In the past 15 kyrs, the caldera floor has been affected by tectonic resurgence causing a maximum net uplift of about 100 m at the La Starza marine terrace which determined the definitive emersion of the terrace at about 4000 years BP (Isaia et al., 2009). Ground movements are also documented during the past 2.0 kyrs (Di Vito et al., 2016 and references therein) and, in particular, since late 1960s, unrest episodes have been recorded by the Osservatorio Vesuviano monitoring system; the largest ones took place in 1969-72 and 1982-84 and generated uplifts of 170 and 180 cm, respectively, and the evacuation of part of Pozzuoli town.

1.2 Somma Vesuvius

The Somma-Vesuvius is a moderate size (1281 m a.s.l.) composite central volcano (Fig. 1). It consists of an older volcano, Monte Somma, dissected by a summit caldera, and Mount Vesuvius, a recent cone developed within the oldest Somma caldera, and possibly grown after the 79 AD “Pompeii” eruption (Fig. 4).
The caldera has a complex shape resulting from several collapses, each related to a high-explosive Plinian eruption (Cioni et al., 1999). It has a quasi-elliptical shape with a 5 km long, east–west major axis. Its northern rim is a well-defined 300 m high steep wall with an average elevation of approximately 1000 m a.s.l. Its southern part is evidenced by a sharp increase in the inclination slope below ~600 m a.s.l. Here the structure is covered by a pile of recent lava flows and pyroclastic deposits that, after filling the caldera, overtopped its lowest rim.
Along the caldera wall a pile of lava flows, spatter and scoria deposits are exposed (Santacroce and Sbrana, 2003) and reflect a dominant effusive activity (Johnston Lavis, 1884; Santacroce, 1987) that prevailed on the explosive, generally low energy events (Cioni et al., 1999). The products of this older (>22 ka) explosive activity are exposed in medial and distal outcrops on the Apennine Chain, always intercalated between the “Campanian Ignimbrite” (from the nearby Campi Flegrei) and the pomici di Base (from Somma-Vesuvius) deposits. One of these medial–distal fallout deposits has been related to a compositionally similar thick pyroclastic unit, the Camaldoli della Torre tuff cone, penetrated by a borehole nearby Camaldoli della Torre eccentric apparatus (Di Renzo et al., 2007; Di Vito et al. 2008). The specific sedimentological characteristics suggest the occurrence of high-intensity explosive volcanism in the Vesuvius area just after the emplacement of the “Campanian Ignimbrite” (Di Renzo et al., 2007).

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The history of the volcano after 22 ka has been characterized either by long quiescence periods, interrupted by Plinian or sub-Plinian eruptions, or by periods of persistent volcanic activity, with lava effusions and Strombolian to phreato-magmatic eruptions, related to the alternation of closed and open conduit conditions, respectively. In particular, the growth of the Vesuvius cone has taken place, although with some minor summit collapses, during periods of persistent low-energy open-conduit activity, the last of which occurred between 1631 and 1944 (Arrighi et al., 2001). The total volume of erupted magmas has been estimated to be ~300 km^3 (Civetta and Santacroce, 1992).

The earliest well-known Plinian eruption (pomici di Base; 22 ka; Cioni et al., 1999 and references therein) determined the beginning of both collapse of the Mt. Somma volcano and formation of the caldera. This eruption was followed by lava effusions that flowed along the eastern slopes of the volcano, and a quiescent period interrupted at 19 ka BP by the pomici Verdoline sub-Plinian eruption. The subsequent long period of quiescence, during which only two low-energy eruptions took place, lasted until 8.8 ka BP, when it was broken by the Plinian pomici di Mercato eruption (Cioni et al., 1999; Mele et al., 2011). A thick

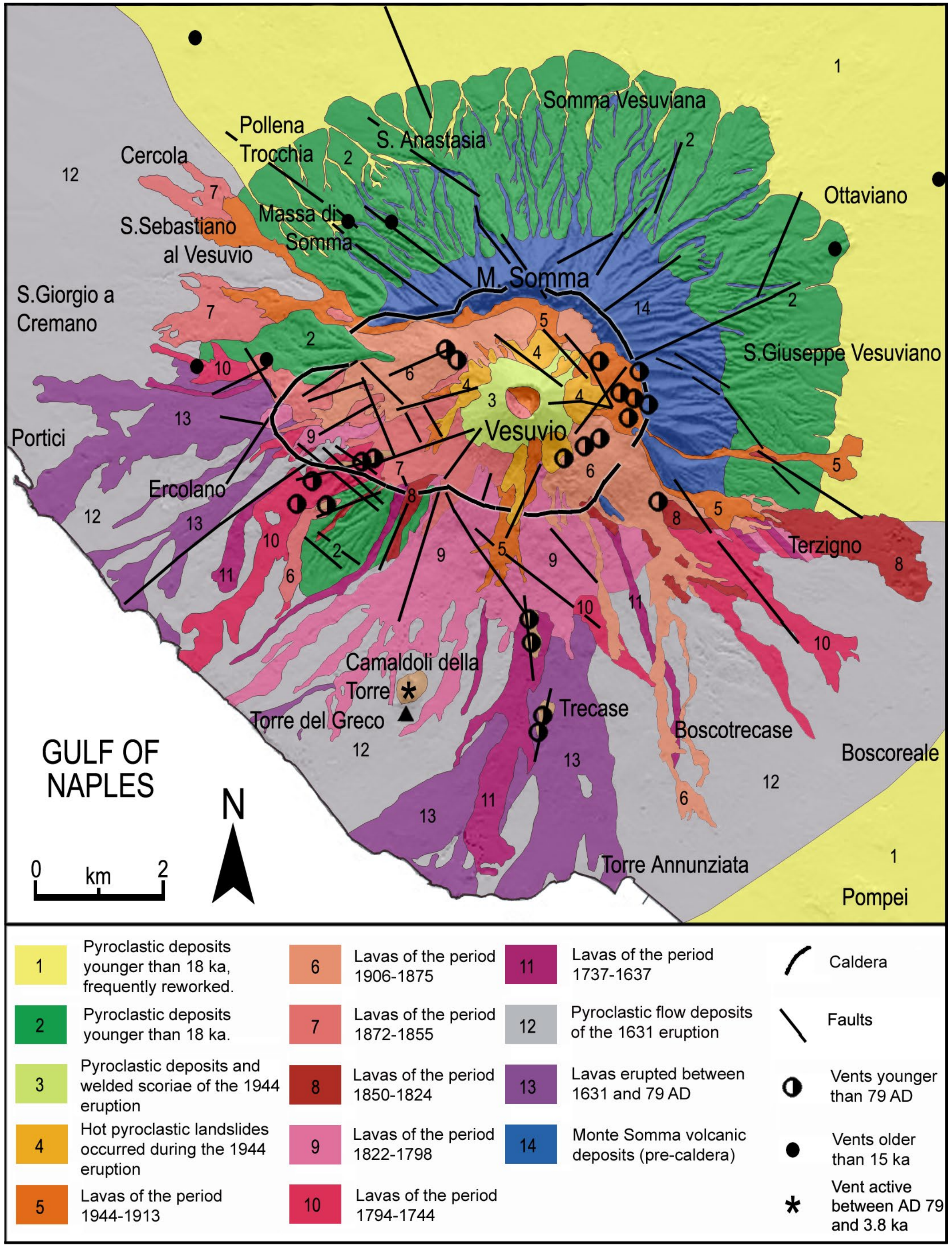

Fig. 4 - Somma-Vesuvius geological sketch map (after Orsi et al., 2003). Structural lineaments after Ventura and Vilardo, 1999).

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paleosol overlying the deposit of this eruption testifies for a further period of quiescence, interrupted only by two low-energy eruptions. This paleosol contains many traces of human presence until the early Bronze Age, and is covered by the deposits of the Plinian pomici di Avellino eruption (3.9 ka) (Cioni et al., 1999; Di Vito et al., 2009; Sulpizio et al., 2010a, b).

The pomici di Avellino eruption is the Plinian event of Vesuvius with the highest territorial impact. It affected an area densely inhabited by early Bronze Age human communities and resulted in the long-term abandonment of an extensive zone surrounding the volcano. Traces of human life beneath the eruption products are very common throughout the Campania Region (Di Vito et al., 2018).

The pomici di Avellino eruption was followed by at least 8 Strombolian to sub-Plinian eruptions, over a relatively short time, and by about three centuries of quiescence, broken by the Plinian 79 AD eruption (Andronico and Cioni, 2002 and references therein). After this eruption, the volcano has generated only two more sub-Plinian events in 472 AD (Rosi and Santacroce, 1983) and 1631 (Rolandi et al., 1993; Rosi et al., 1993), and low-energy open-conduit activity between the 1st and 3rd, 5th and 8th, 10th and 11th centuries, and between 1631 and 1944 (Arrighi et al., 2001 and references therein).

Since the last of 1944, Vesuvius is quiescent, as it has not shown signs of unrest and only moderate seismicity and fumaroles testify its activity.

All Plinian eruptions of Somma-Vesuvius were characterized by vent opening, sustained column and pyroclastic flow and/or surge phases, and were accompanied by volcano-tectonic collapses. Sustained columns, which reach maximum heights of about 30 km, generated widespread fallout deposits (Fig. 5) with volumes between 1.5 and 4.4 km^3 DRE of magma. Pyroclastic currents with volumes of magma between 0.25 and 1 km^3, DRE, are distributed along the volcano slopes and within the surrounding plains (Fig. 5), reaching maximum distances of over 20 km from the vent (Cioni et al., 2003; Gurioli et al., 2010). In proximal areas, thick breccia deposits were produced during the caldera collapse.

Among the sub-Plinian eruptions of Vesuvius, only the 472 AD and the 1631 events are studied in details (Rosi and Santacroce, 1983; Rolandi et al., 1993; Rosi et al., 1993). They are characterized by alternation of sustained columns and pyroclastic flow and/or surge generation. Sustained columns are less than 20 km high and pyroclastic currents travel distances not in excess of 10 km. Fallout deposits of both Plinian and sub-Plinian eruptions are generally dispersed to the east of the volcano (Fig. 5), depending on the main wind directions (Cioni et al., 2003). The occurrence of a caldera collapse may be related to the partial or complete emptying of the magma chamber. Each eruption shows trace of the intervention, during the caldera

collapse phases, of fluids from the hydrothermal system related to the magma chamber. This causes abrupt changes in the dynamics of the events, so triggering hydrothermo-phreatomagmatic processes that reinforce the explosive energy. In the 79 AD eruption, the beginning of the caldera collapse is marked in fact by a "hydrothermo-magmatic" phase producing widespread turbulent pyroclastic flows and is followed by the emplacement of coarse lithic-enriched debris flows, possibly from a multiple vent system. Similarly, in the pomici di Base eruption, debris flow deposits and pyroclastic surges driven by hydrothermal-phreatomagmatic activity mark the syn-caldera phase.
The quiescence periods preceding the Plinian eruptions last from few centuries to millennia.

1.2.1 Volcaniclastic debris flows related to Vesuvian eruptions

The repeated and intense explosive activity of Neapolitan volcanoes has generated wide blankets of loose pyroclastic deposit covering both volcanic edifices and areas located downwind. The prevailing W-E wind field allowed a thick tephra deposition over the Apennine chain and topographic gradient and intense precipitation both over the volcano edifices and Apennine chain and the presence of loose to poorly-consolidated volcaniclastic material predisposes the condition for producing sediment-laden flows, including flood and debris flows (Rosi et al., 1993; Zanchetta et al., 2004a; Di Vito et al., 2013; 2018). At Somma-Vesuvius, during eruptions or shorty after them (i.e. syn-eruptive events) there are historical accounts, which demonstrated the occurrence of sediment-laden flows along the slopes of the volcanic edifice and within the Apennine chain (Rosi et al., 1993). The

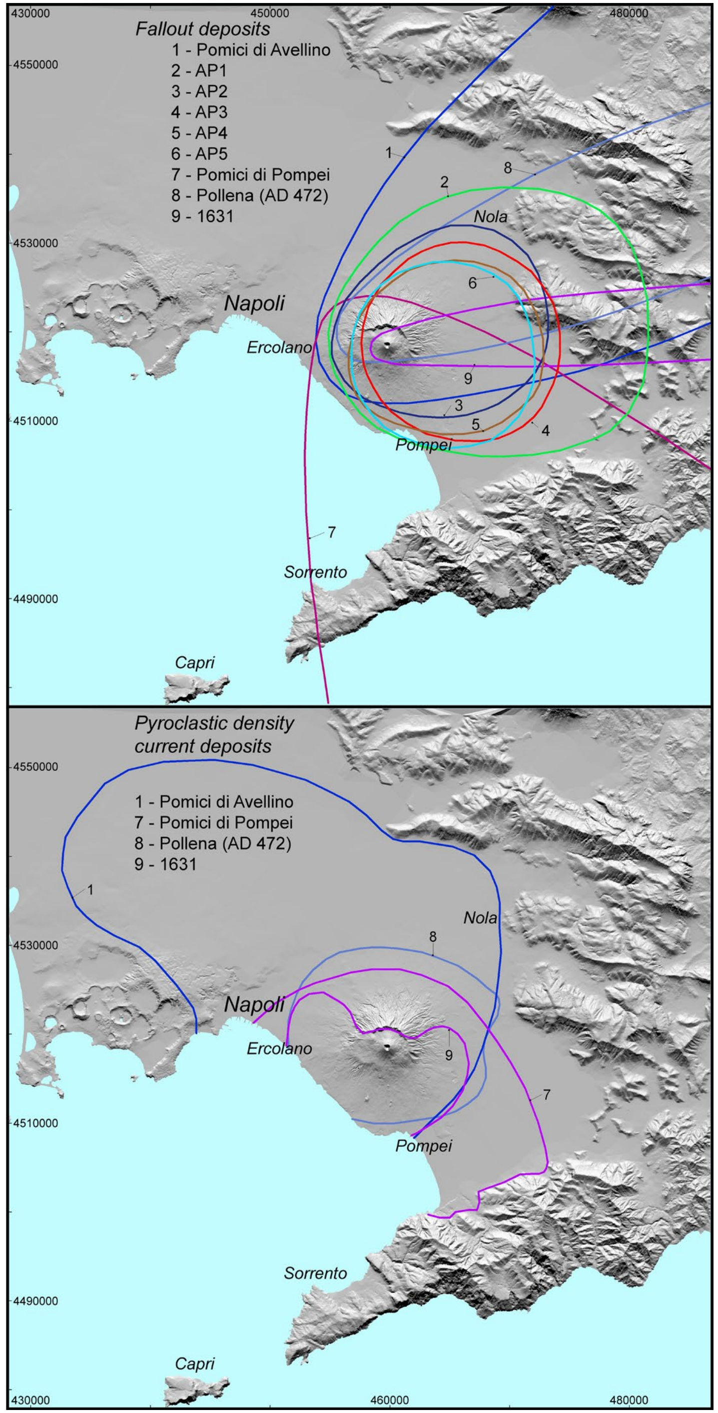

Fig. 5 - Distribution of Plinian and sub-Plinian deposits of Somma-Vesuvius eruptions of the past 10 kyrs (after Di Vito et al., 2013).

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construction by Bourbon kingdom of an efficient drainage system, the Regi Lagni network, both along valleys of Somma-Vesuvius edifice and in the Campanian Plain to prevent flooding owing to the persistent volcanic activity of Somma-Vesuvius after 1631 AD is the most evident mitigation action undertaken in the region during historical time.

Geological information gives us the most sound evidence of syn-eruptive debris flows associated to the main explosive eruption of Somma-Vesuvius during the Late Pleistocene-Holocene (Zanchetta et al., 2004b; Sulpizio et al., 2006; Di Vito et al., 2013; 2018). Syn-eruptive debris flows deposits usually directly overlie the primary pyroclastic deposits (in the Apennine chain mostly constituted by pyroclastic ash and lapilli fallout beds) and are characterized by homogenous lithological composition similar to the related primary pyroclastic deposits (Zanchetta et al., 2004a; Sulpizio et al., 2006). However, late stages of remobilization can also include products of older eruptions as progressive exhaustion of primary volcanic deposits along the slopes and channels occurs (Di Vito et al., 2018). Following the first phase of rapid remobilization of loose pyroclastic deposits after the eruption, volcaniclastic material can be locally stabilized (i.e. vegetation and soil development) and preserved for long time and made available for post-eruptive remobilization.

Over the Apennine chain downwind of Campanian volcanoes this intra-eruptive activity has been dramatically testified by soil slip/debris flow processes, as in the recent dramatic cases of 1998. Historical accounts report tens of events since the last centuries (Migale and Milone, 1998, Calcaterra et al., 2003a). The triggering mechanisms are substantially different from syn-eruptive debris flows related to rapid remobilization of pyroclastic material (Sulpizio et al., 2006). They have been extensively studied (e.g. Del Prete et al., 1998; Pareschi et al., 2000, 2002; Calcaterra et al., 2003a, b; Zanchetta et al., 2004b; Di Martire et al., 2012; De Vita et al., 2017). Analysis of historical accounts on occurrence and distribution of debris flow events shows a strict relationship between Holocene explosive eruptions with wide pyroclasts dispersion and debris flow generation (Bisson et al., 2007), indicating that out of the depositional area of pyroclastic products there is a rare occurrence of debris flows in the Campanian Plain. This allows a first regional hazard mapping of the Campania region.

However, mechanisms to pass from "syn-eruptive" to "post-eruptive" are unclear and this specific point needs to be investigated in detail in the next future. Probably debris flows hazard can last months to years after an eruption and estimation of time of stabilization is hence of great interest to assess risk and prepare mitigation plans.

1.3 Ischia

The island of Ischia represents the top of a volcanic system that rises more than 1,000 m from the sea floor, in the north-western part of the Gulf of Naples. It covers an area of about 46 km^2 and reaches a maximum height of 787 m a.s.l., in correspondence of Mt. Epomeo, located in the central part of the island.

Ischia is a volcanic field that, in the course of its history, has profoundly changed its appearance several times even recently. The island is composed of volcanic rocks, deposits of landslides and, subordinately, sedimentary rocks, reflecting a complex history of alternating constructive and destructive phases, due to the interaction between tectonism, volcanism, volcano-tectonism and surface gravitational movements (Vezzoli, 1988; Orsi et al., 1991; 2003; de Vita et al., 2006; de Vita et al., 2010; Sbrana and Toccaceli, 2011; Della Seta et al., 2012).

The volcanic rocks found on the island are the product of effusive eruptions, which formed lava flows and domes, and both magmatic and phreatomagmatic explosive eruptions, which generated extensive layers of ash- and lapilli-fallout, ignimbrites and dilute and turbulent pyroclastic density current deposits, often transformed in tuffs by post-depositional processes of alteration.

The age of onset of volcanic activity on the island is not precisely known, as the oldest dated rocks, which are not the oldest exposed, have an age of 150 ka and belong to a volcanic complex, currently partly dismantled and covered by the products of the most recent activity. The remnants of this edifice are exposed in the southeastern sector of the island.

Between 150 and 74 ka this activity was accompanied by the formation of small lava domes, presently located along the coasts of the island. The following period of activity was characterized by the highest-magnitude explosive eruptions occurred on the island, intercalated with less energetic episodes, and culminated at 60-55 ka with the eruptions of the green tuff of Mt. Epomeo (Brown et al., 2008; Sbrana and Toccaceli, 2011). These highly explosive eruptions are responsible for the formation of a caldera that probably occupied the area where the central part of the island is currently located (Rittmann, 1930; Rittmann and Gottini, 1980; Vezzoli, 1988). The green tuff is exposed at M. Epomeo and along the reliefs in the central part of the island.

After the eruptions of the green tuff, volcanism continued with a series of explosive eruptions, up to about 33 ka, fed by vents located along the south-western and north-western edges of the island. The rocks originated during these eruptions mantle the western and south-western slopes of Mt. Epomeo and are exposed along the western coast of the island.

The long period of quiescence that followed, ended at about 28 ka with a low-energy explosive eruption, which took place along the south-eastern coast of the island. Subsequently, the volcanic activity continued sporadically up to 18 ka with the emission of magmas that fed effusive and explosive eruptions (magmatic and phreatomagmatic), with the emplacement of lava flows, pyroclastic-fall deposits and the construction of small tuff-rings and tuff-cones. The rocks belonging to this period of activity are well exposed along the southern and southeastern coast of the island.

Meanwhile, the geography of the island was deeply changing also due to the uplift of the green tuff caldera floor, which started as the result of a repeated episodes of intrusion of new magmas into the system (Rittmann, 1930; Rittmann and Gottini, 1980; Orsi and Chiesa, 1988; Orsi et al., 1991; Luongo et al., 1995; Tibaldi and Vezzoli 1997; Tibaldi and Vezzoli 1998; Acocella and Funiciello, 1999; Molin et al., 2003; Carlino et al., 2006). With its uplift in the order of about 900-1100 m, very rarely recognized in other volcanic areas, Ischia is one of the most evident, better studied and known cases of intracalderic resurgence. The resurgent area has a polygonal shape resulting from the reactivation of regional faults and the activation of faults directly related to volcano-tectonism (Orsi et al., 1991; Acocella and Funiciello, 1999), which dismembered this area in a series of differentially displaced blocks. The result is an asymmetrical block structure, with a maximum uplifted block in the northwestern part of the resurgent area (Rittmann and Gottini, 1980; Vezzoli, 1988; Orsi et al., 1991; Acocella and Funiciello, 1999; de Vita et al., 2006; de Vita et al., 2010; Della Seta et al., 2012).

Resurgence strongly influenced volcanic activity for at least the last 10 ka, determining the conditions for the ascent of magmas only in the eastern sector of the island and along pre-existing regional fault systems. In fact, after a period of quiescence started at about 18-15 ka, volcanism on the island resumed at 10 ka, starting the last period of activity. This period was characterized by both effusive and explosive very intense volcanic activity. In particular, the products of 46 different eruptions were recognized, mainly concentrated in the period between about 3 ka and 1302 AD. (de Vita et al., 2010). These eruptions produced lava flows and domes, pumice- and scoria-cones, tuff-rings and tuff-cones, and pyroclastic-fall and -flow deposits more or less widely distributed. The most recent studies conducted on the island have shown that in the last 10 ka periods of quiescence, also plurisecular, alternated with periods of intense eruptive activity.

As volcanism is directly connected to the dynamics of the resurgence of M. Epomeo, it is deduced that this phenomenon has not been continuous over time, but has been achieved through intermittent phases of uplift and tectonic quietness. The reactivation of faults and the related renewal of volcanic activity were systematically accompanied by the formation of landslides, sometimes also colossal (debris avalanche), whose deposits are

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intercalated at various heights in the stratigraphic series, preceding and following the deposits of the main volcanic eruptions. These deposits identify periods of intense erosion and redeposition of primary volcanic deposits and show that the instability conditions of the slopes were induced by the same vertical movements responsible for the formation of faults and fractures that fed volcanism (de Vita et al., 2006; 2010; Della Seta et al., 2012).

At present, geodetic data show a generalized subsidence of the Mt. Epomeo block, at least in the last decades, suggesting that currently the process of resurgence is at rest (de Vita et al., 2006; Manzo et al., 2006; Sepe et al., 2007).

1.3.1 The Ischia slope instability

Caldera resurgence, volcanism and slope instability were not frequently related to each other in the literature, although since the first years of the 21st century also caldera resurgence has been suggested as a possible cause of slope failure (Chiocci et al., 1998; Tibaldi and Vezzoli, 2004; Chiocci and de Alteriis, 2006; de Vita et al., 2006; Della Seta et al., 2012).

The island of Ischia gives a good opportunity to investigate these phenomena and related effects, as it is the only documented example of resurgent caldera in which, during uplift, volcanism and generation of mass movements have been very active and linked in a sort of cyclical behavior (Fig. 6; de Vita et al., 2006).

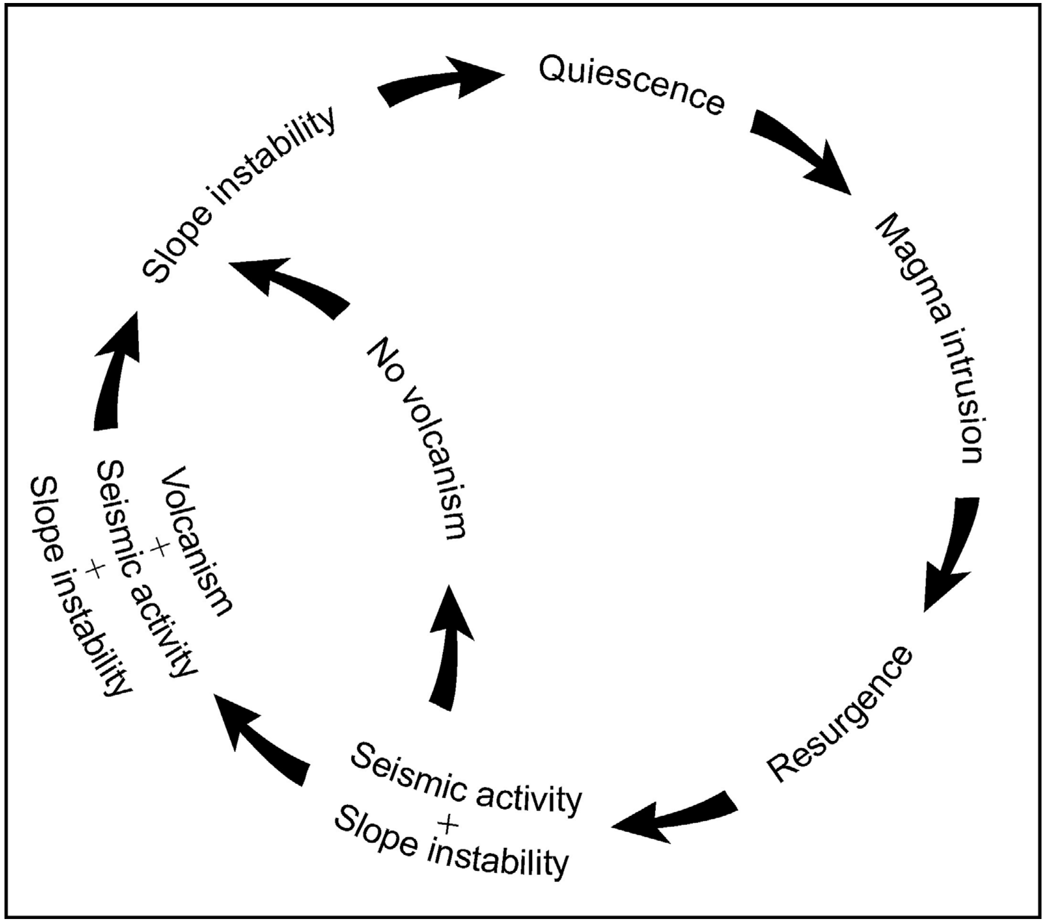

Fig. 6 - Cyclical behavior of phenomena occurring at Ischia at variable time intervals. Starting from a quiescence period, a new magma intrusion triggers resurgence, and therefore deformation, which is accompanied by seismicity and slope instability. Renewal of volcanism may or may not occur, being accompanied and followed by seismic activity and slope instability. Slope instability could last many centuries, during the following quiescence period (after de Vita et al., 2006).

According to Della Seta et al. (2012), slope instability deposits exposed at Ischia can be grouped in two classes, based on the surface covered by the deposits and on their lithological and sedimentological characteristics (Fig. 7): Class 1 includes debris/rock avalanches, larger debris flows (lahars), covering areas larger than 0.2 km^2, and a Deep Seated Gravitational Slope Deformation (DSGSD); Class 2 includes relatively smaller mass movements, affecting areas up to 0.2 km^2, namely rock falls, slumps, slides and smaller debris flows (lahars). Some landslide deposits cropping out at Ischia are intercalated to volcanic deposits younger than 10 ka (Tibaldi and Vezzoli, 2004; de Vita et al., 2006), while others contain remains of artifacts of ancient human settlements, since the island was inhabited by communities organized as early as the 13th century BC (Buchner, 1943; Buchner, 1986; Buchner et al., 1996). To these evidences are added the numerous historical chronicles, the most ancient of which date back to the 4th century BC (Di Martire et al., 2012 and bibliography reported therein). The temporal distribution of landslides recorded at Ischia, in relation to primary volcanic deposits, shows how the so called Class 1 deposits are documented only up to the 2nd-3rd century AD (Fig. 8).
While the intercalated landslide deposits are concentrated in the eastern and southern sectors of the island, the northern and western sectors are dominated by the deposits of large debris/rock avalanches (Della Seta et al., 2012) generated by the failure of rock masses affected by Mass Rock Creep (MRC). The largest of these deposits (125 million m^3 in volume) is a rock avalanche that buried the area presently occupied by the town of Forio and reached the sea, travelling as far as three km in the western Ischia offshore (Sbrana and Toccaceli, 2011; Della Seta et al., 2012).
In historical reports (Del Prete and Mele, 2006 and references therein) a huge collapse of the western flank of Mt. Epomeo is cited. This slope instability episode has been correlated in the literature to the deep seated gravitational slope deformation (DSGSD; Della Seta et al., 2012) affecting Monte Nuovo, and interpreted as the consequence of a MRC process (Della Seta et al., 2015).

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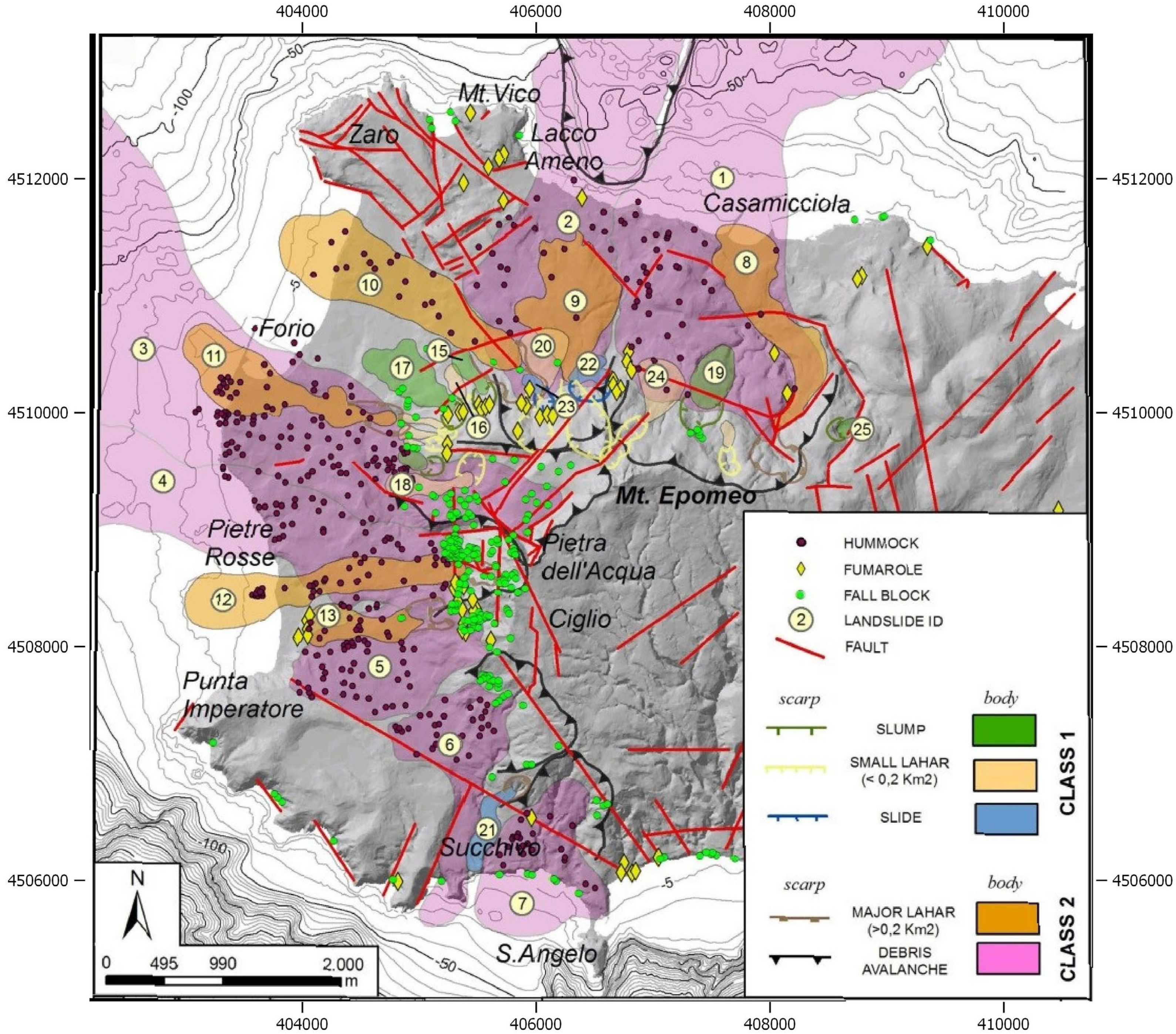

Fig. 7 - Class 1 and Class 2 landslide deposits and their distribution in the morphostructural map of the northern and western slopes of Mt. Epomeo (modified after Della Seta et al., 2012). Circled numerals refer to mass movement ID: 1 Casamicciola DA; 2 Lacco Ameno DA; 3 Falanga DA; 4 Pietre Rosse DA; 5 Citrunia DA; 6 Ciglio DA; 7 Succhivo DA; 8 Casamicciola lahar; 9 07.1228 lahar; 10 S. Francesco lahar; 11 Forio lahar; 12 Citara lahar; 13 Cuotto lahar; 14 Mt. Nuovo DSGSD; 15 MN-A; 16 MN-B; 17 MN-C; 18 MN-D; 19 03.04.1881; 20 02.02. 1828; 21 Chiarito debris and rock slide; 22 07.28.1883 a (debris slide); 23 07.28.1883 b (debris slide); 24 12.14.1797; 25 07.28. 1883 c (slump) (DEM resolution, 5 m).

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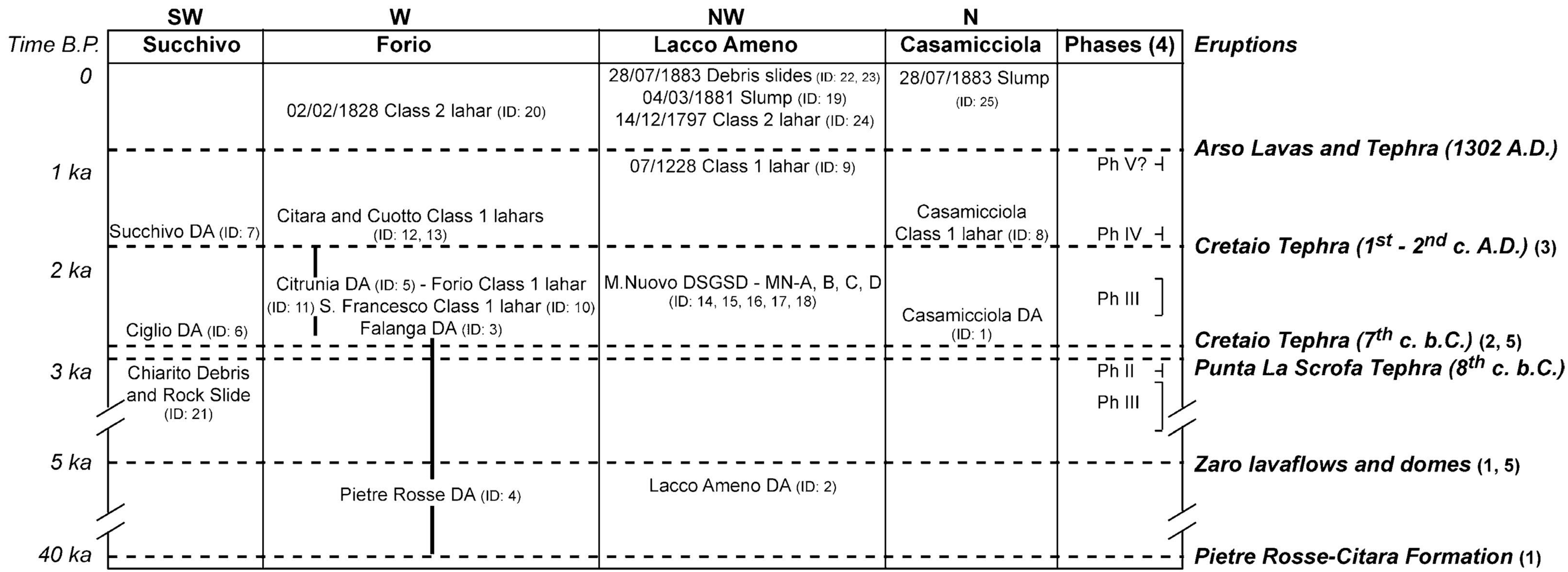

Fig. 8 - Temporal distribution of landslides recorded at Ischia, in relation to primary volcanic deposits (after Della Seta et al., 2012).

2. The recent landslide events

On May 5th 1998 a 16-hour prolonged heavy rainfall triggered a huge number of slope failures towards the towns of Quindici, Bracigliano, Siano, Sarno and San Felice a Cancello. As a matter of fact, the catastrophic events involved an extension area of around 60 km^2 and a volume of more than 2,000,000 m^3 (40% derived from the materials eroded along the channels), leading to 160 victims and huge damage to the quoted towns (Fig. 9).
The population was fully unaware of the possible risk linked to slope failure in case of heavy rains, neither aware and prepared to emergency were local authorities. Evacuation started late, and in a very disorganized way: even the Sarno hospital was partly buried and collapsed by one of the so called “mud-flows”, and some

doctors who were trying to help injured people, died therein while doing their job. The occurrence of these landslides signed a severe turn for the Italian scientific community: since then, hundreds of scientific papers have been published dealing with the possible triggering mechanisms, the geotechnical features of involved materials, the role of hydraulic circulation as a control factor.

Fig. 9 - The 1998 landslides at Pizzo d'Alvano. At the footslopes, the Episcopio hamlet, Sarno municipality (Legambiente, 2018).

The slope failures remobilized the cover of the limestone reliefs, mainly made up of pyroclastic fall deposits of Somma-Vesuvius, even though, moving towards the Palma Campania hillslopes, also Campi Flegrei pyroclastic fall deposits were involved. The primary blanket was not continuous over the limestone belt: in many sites, in fact, past water- and gravity-driven phenomena had already remobilized it. As far as the triggering mechanisms are concerned, the scientific world is still far from sharing a common opinion: according to Pareschi et al. (2000), the drainage network typology, the slope angle and the basin shape are the key factors for the triggering stage. Di Crescenzo and Santo (2005) highlight the role that fresh track cuts and denudated slopes have in the detachment mechanism. Finally, other authors (Calcaterra et al., 2000; De Vita and Piscopo, 2002) pinpoint the importance of ground circulation in both the pyroclastic cover and the karst cavities in the limestone bedrock, and of strong variations in hydraulic conductivity in the first meters of the mantling deposits-limestone succession, as a factor controlling landslide occurrence.

When looking at the dynamics of their occurrence, most of these landslide phenomena begin as soil-slides, with the remobilization of even a thin pyroclastic and paleosol blanket mantling the slope flanks. These initial slides usually start from hollows (Hack, 1965), small elongate depressions within the bedrock of colluvium mantled hillslopes. They have no obvious stream channel but serve as drainage lines. Usually, hollows are parts of zero-order basins, slope units which conjoin a slope and a stream (Tsukamoto, 1973), located headward of first-order channels. The passage from initial slides to a debris flow is favoured by channelling of the remobilized mass in a pre-existing stream channel: when this occurs, the flow is confined in the hydrographic cut and further sediment can be removed during the movement of the sliding mass, which can bulk due to the basal scouring by the moving flow, erode the gully banks (Zanchetta et al., 2004b), and cause other landslide phenomena, linked to retrogressive erosion, which sum up their effect, supplying material to the main debris flow.

When slides occur along an open slope they assume the features of a debris avalanche (Hungr et al., 2005), caused by the further progression of debris: in absence of an established channel, channelling of the removed mass is prevented and the movement occurs along the flanks of the relief denudating a progressively larger area towards the footslope of the mountain. This is the reason why debris avalanches often have the typical shape of an isosceles triangle with an apex angle around 20° (Di Crescenzo and Santo, 2005).

Under a more strictly volcanological point of view, both debris flows and debris avalanches can be considered lahar phenomena; as a matter of fact, given the long time passed since the last explosive event at Campania volcanoes, able to emplace pyroclastic fall deposits on the limestone relief and induce severe changes in the drainage network, the 5th May 1998 debris flows, the 4th March 2005 Nocera debris avalanche, as the numerous similar phenomena which yearly occur along the limestone belts bordering the Campanian plain, can be classified as inter-eruptive lahar events. Hence, debris flows linked to the presence of active volcanoes in Campania protract the hazardous effects of volcanic eruptions for many centuries.

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Day 1st: impact of historical and recent debris flows

Stop 1.1: Villa di Augusto at Somma Vesuviana (451482 E, 4525137 N)

Significance: Syn-eruptive debris flows related to the Pollena eruption and their impact on Roman structures and buildings. Discussion points: timing of debris flows occurrence and their relationships with the primary deposits, impact on buildings.

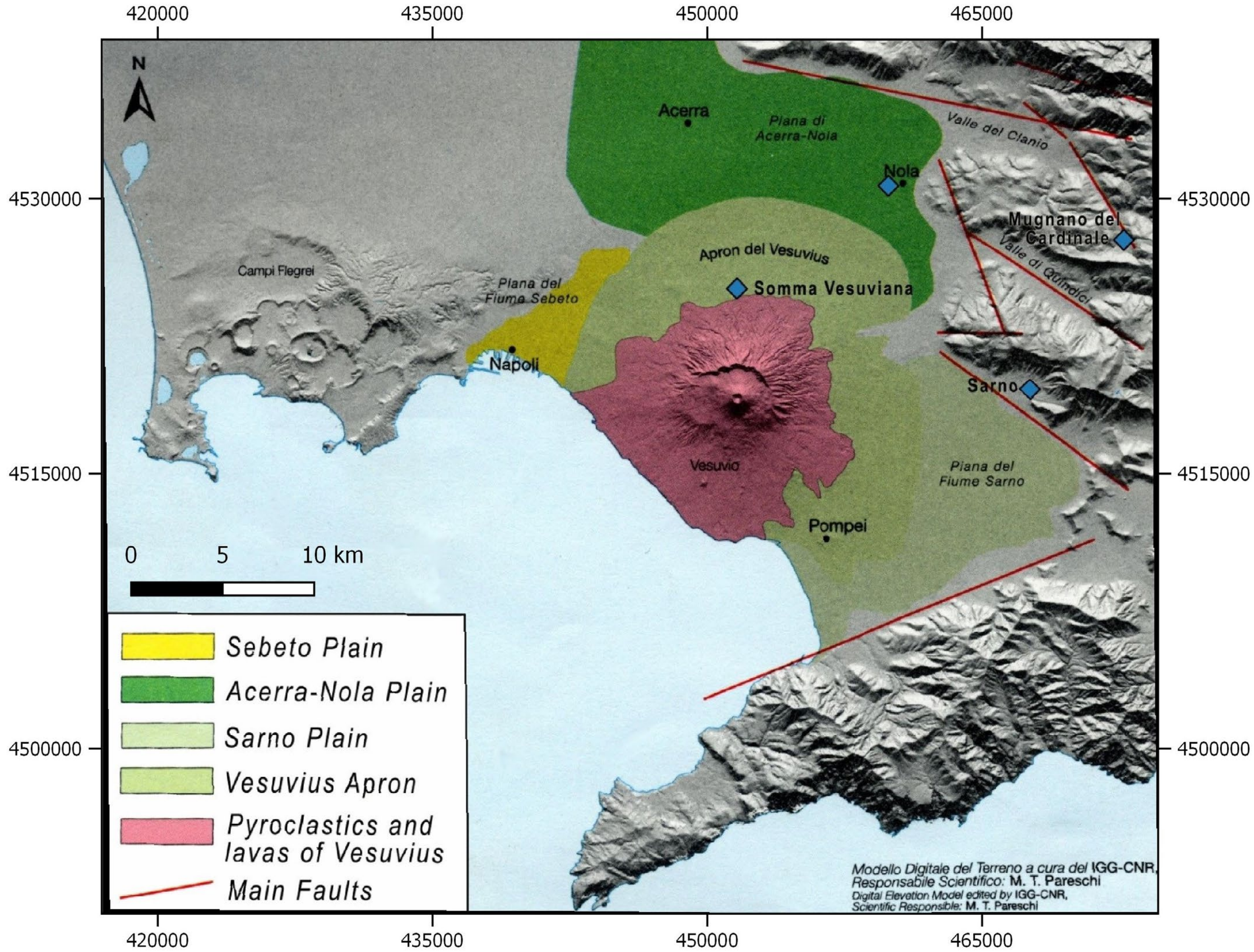

Fig. 10 - Sketch map of the Vesuvius edifice and the surrounding plain and Apennines. The Villa di Augusto is located in the northern sector of the Vesuvius Apron, the Nola Amphitheater in the Nola Plain at the mouth of the Quindici Valley-Vallo di Lauro.

The archaeological site is a rectangular trench 30 by 35 m, located within the Vesuvius volcaniclastic apron as defined by Santacroce and Sbrana (2003). The elevation of the site is 130 m a.s.l. The apron is a semicircular area with a low angle slope (with mean slope between 10° and 5°) surrounding the edifice and connecting the volcano edifice with the plain (slope between 2° and 0°) (Fig. 10). This area is characterized by a complex intercalation of primary pyroclastic deposits emplaced by both fallout and minor PDCs, and volcaniclastic deposits dominated by debris- and hyperconcentrated-flows deriving from a more or less rapid erosion of primary deposits.

The excavations began in the late twenties of the last century, following the fortuitous discovery of Roman walls during agricultural work. Given the monumentality of the structures that emerge from the first excavations, the villa was immediately interpreted as the property of a high rank person and, on the basis of written sources which place in "the neighborhood of Nola" the residence where the emperor Augustus died, attributed the villa to his home.

At this time, it is not possible to confirm the attribution of this edifice to the Emperor Augustus. Finally, the different ages and wealthy functions of the various parts of the building suggest that it was originally built as a very important mansion (1st century AD?), modernized until the 3rd century AD and then in the 5th century AD it was transformed into a farm (Perrotta et al., 2006).

An area of about 2,500 square meters has been excavated, but it is conceivable that the complex entirety extends for about 25,000 square meters. What we see makes us think of a monumental entrance to a large villa, which at an advanced stage of its life produces wine. The wine cell preserves containers whose complete capacity is calculated around 100,000 liters. The portal with tympanum shows a decoration with stuccowork with elements of the religiosity of the god Dionysus, usually linked to wine and a statue of the god had to be in one of the niches, while in the opposite one was found a statue of a woman. During excavations casts are exposed, while the originals are kept at the Museum of Nola.

One of the apses preserves a rare testimony of the 3rd century AD Roman painting, with the representation of nymphs and marine animals. Of particular interest is the presence of Christian symbols on the walls of the second apse. The area was strongly affected by the eruption of Pollena in 472 AD, when it was in part already abandoned, perhaps after the raids by the barbarians at the beginning of the 5th century AD.

The exposed sequence of deposits that buried the Villa is made up of seven stratigraphic units, defined by Perrotta et al. (2006) A to G, from base upwards (Fig. 11). These units are separated by paleosols and each unit includes a single deposit or a succession of deposits of different origins.

Four units (B, D, F and G, Fig. 11) are composed exclusively of pyroclastic products emplaced during the following explosive events: 512 AD, Medieval (7th-12th cent.) and 1631 and 1906 (?) AD eruptions.

Unit A is composed of both pyroclastic units (units A1-A6) of the 472 AD eruption and volcaniclastic deposits (units A7-A13), emplaced by syn-eruptive debris flows soon after the eruption.

Syn-eruptive debris-flows in the same stratigraphic position have been found along all the northern plain up to about 18 km from the Vesuvius crater (Di Vito et al., 2018). As in the villa area they buried a dominantly cultivated area. Unit C is interpreted as inter-eruptive debris flows (in the sense of Zanchetta et al., 2004; Sulpizio et al., 2006).

Stop 1.2: Nola Amphitheater Laterizio (459691 E, 4530851 N)

Significance: historical debris flows in the Campanian Plain. Discussion points: impact of debris flows on distal areas, landscape modifications, timing of phenomena.

The site (Fig. 10) is representative of an area partially abandoned before the 472 AD eruption and at the age the amphitheater was undergoing a phase of plunder. The eruption impacted this depressed area with accumulation of fallout and a thick sequence of syn-eruptive debris flows.
The city of Nola, built in the central part of the Campanian Plain in the 8th century BC and inhabited by indigenous people with a strong Etruscan and Greek presence, became an important Samnite center. The city was conquered by the Romans at the beginning of the 1st century BC. Around 80 BC new urban walls were built on the north side of the city and on them lies part of the amphitheater, which underwent several renovations until the moment when it was abandoned at the beginning of the 5th century AD.

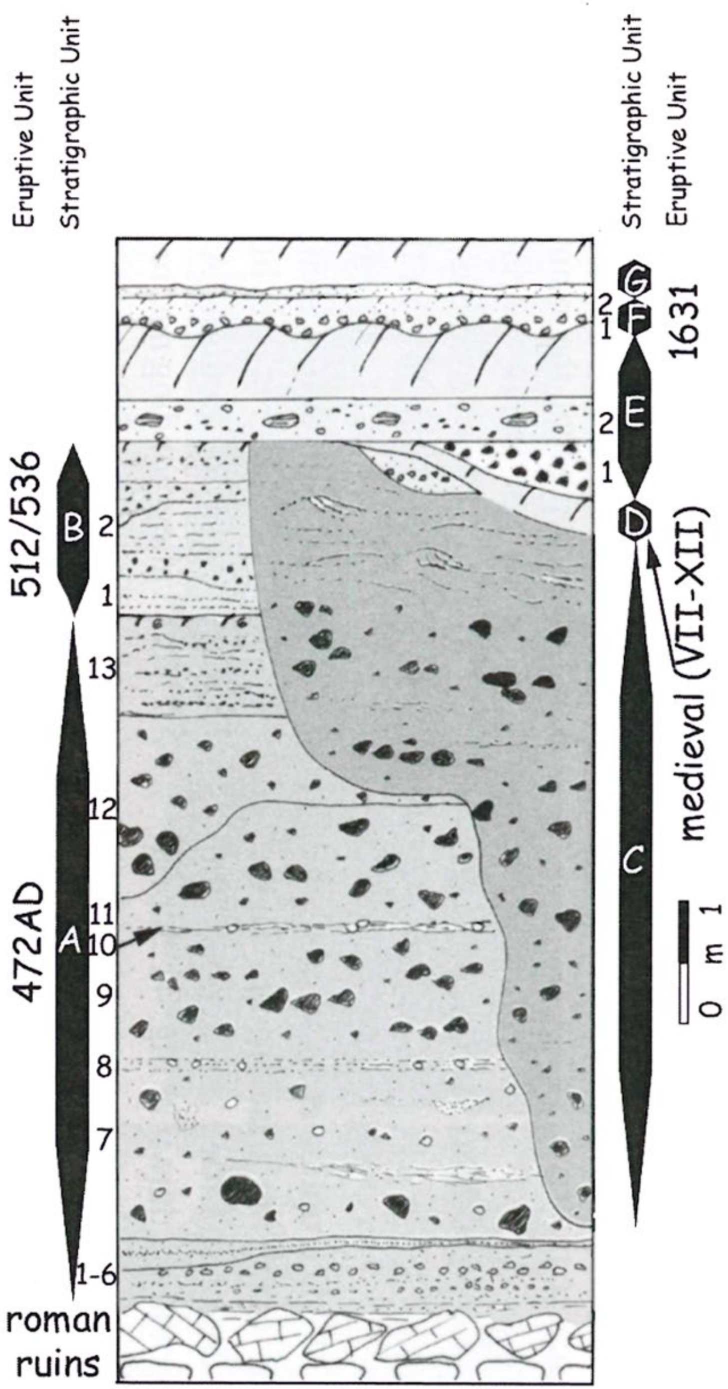

Fig. 11 - Stratigraphic sequence burying the Villa di Augusto (modified after Perrotta et al., 2006). Capital letters indicate stratigraphic units that are divided into layers or beds identified by a number. A1-6, pyroclastic deposits of the 472 AD eruption, A7-13 sequence of syn-eruptive debris flows of the 472 AD eruption, C, inter-eruptive debris flows.

The name Amphitheater Laterizio (made by bricks), was given by the Nola humanist Ambrogio Leone, who published a volume in Venice in 1514 entitled "De Nola", in which he describes the remains of antiquity that are still visible during his time. It is to be supposed that the upper arches, now lost, had to show a wide use of bricks at the time. The amphitheater is one of the largest in Italy, developing on a major axis of 138 m and a minor one of 108 m. The bleachers are preserved only for the lower and middle parts of the *cavea*. Along the outer parts it still shows the colored stucco that had to imitate marble slabs. The *arena* is still surrounded by the parapet plastered with marbles. At the time of the Pollena eruption in 472 AD the amphitheater was abandoned and in a plunder phase.

Today only a portion has been brought to light, but it is clearly perceptible that it is conserved throughout the ellipse.

The sequence of deposits exposed in the area of the Amphitheater (Fig. 12) is composed from base upward by (Fig. 13):

- Paleosol with a variable thickness containing a large amount of bricks, potteries, pieces of concrete, marbles formed both inside and outside the monument during the abandonment and spoliation phase (A in Fig. 13).
- Sequence of coarse and fine fallout deposits (L1-L9 of Sulpizio et al., 2006) and the final ash bed Sy (B in Fig. 13) overlain by an erosional surface produced by the overlaying debris flows.
- Sequence of at least 4 syn-eruptive debris flow deposits

Fig. 12 - The entrance of the Amphitheater Laterizio in the center of the Nola city.

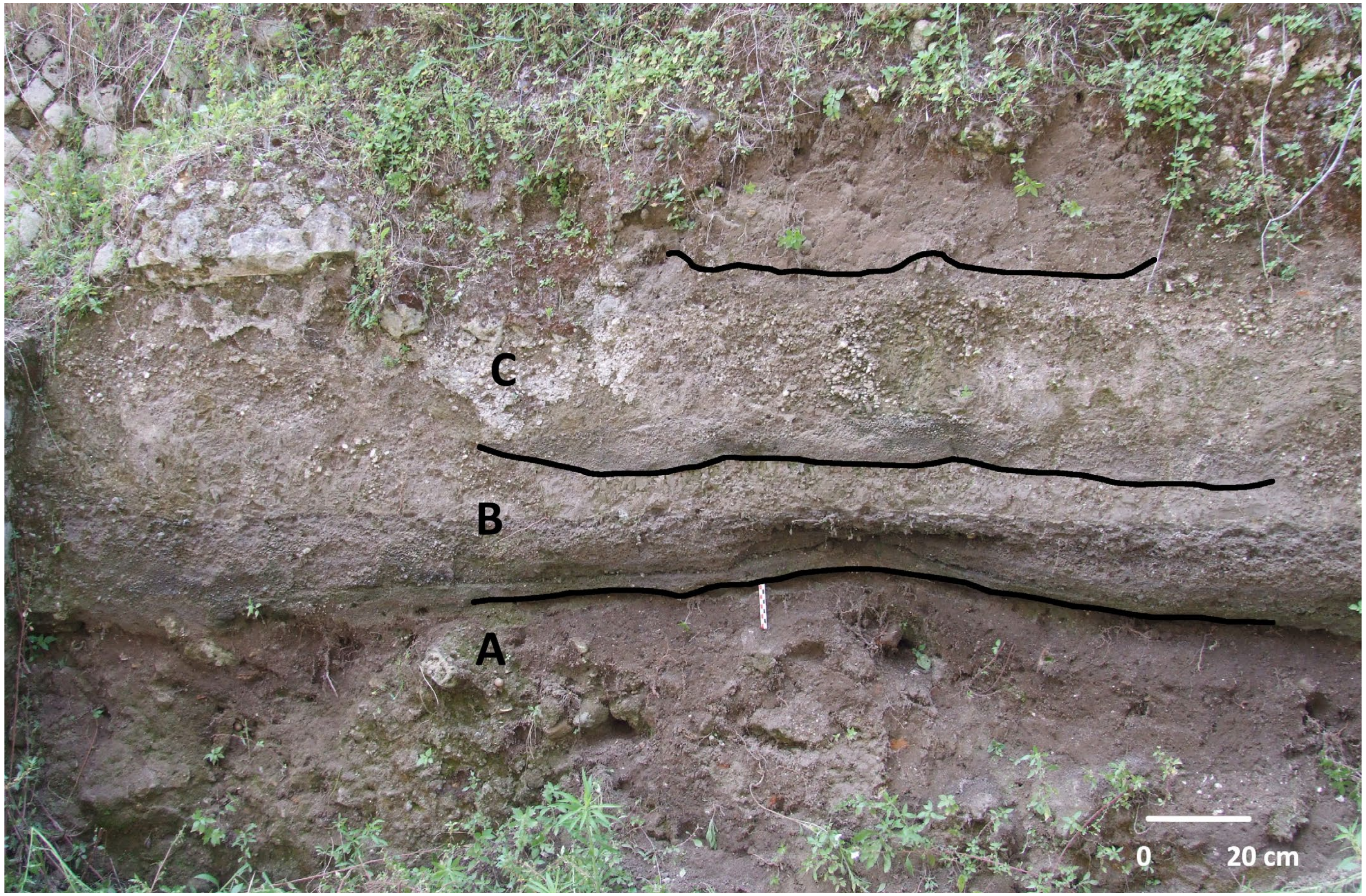

Fig. 13 - Sequence of deposits of the 472 AD eruption near the entrance of the monument. A, paleosol covering the monument floor and containing many tuff bricks and pottery fragments testifying to the abandonment state at the time of the eruption; B, fallout deposits of the eruption including the final ash bed; C, syn-eruptive debris flows overlain by recent reworked deposits and layers of wall collapse.

(C in Fig. 13 and 14) filling the preexisting depression and including blocks of walls, tails, marbles, and blocks of the underlying ash.

Stop 1.3: Sarno (467440 E, 4519874 N)

Significance: syn-eruptive debris flows related to the 1631 AD eruption, and their relationships with the primary deposits along the Apennine valleys. Recent debris flows (May 1998) and their impact. Discussion points: syn-eruptive/ post-eruptive debris flows, timing, distribution, impact, risk mitigation actions.

After the event of May 1998 the construction of a new drainage system over the alluvial fan where the village of Episcopio is built (Zanchetta et al., 2004) cut a sector of fan produced by aggradation of several debris flow deposits resting directly on the 1631 AD fallout (Fig. 15) (Sulpizio et al., 2006). The fan is composed by several debris flow deposits (Fig. 16) mostly formed by lithic and juvenile material of the 1631 AD fallout and minor carbonate clasts from the substrate. Several bodies range from amalgamated and separated by a thin layer of mud, or by thin scour and fill deposits produced during the late stage of the flow and/or during rainy events between debris formation. This suggests a very rapid aggradation of these bodies in a period of high availability of material. These deposits cannot be confused with a later post-eruptive deposit, which shows a more mixed lithology of the juvenile fraction, more similar to present soils over the basin catchment (Zanchetta et al., 2004a, b; Sulpizio et al., 2006). Migale and Milone (1998) report information from historical chronicles that Episcopio was impacted by debris flows in 1637 AD, that is ca. 6 years after the eruption.

Fig. 14 - Sequence of deposits of the 472 AD eruption in the inner part of the monument. The inner part of the Amphitheater is completely filled by syn-eruptive debris flows (C). The base is not exposed.

Engineering risk mitigation measures have been built after the active period of debris flows in the Sarno areas severely affected in 1998, with the main aim of reducing landslide risk (Versace et al., 2008a). The expected effects of these measures can be summarised as follows:

- to reduce the sliding susceptibility in the zones prone to detachments along the slopes;
- to prevent erosion at the base and along the slopes of gullies and reduce the sediment feeding of possible future landslides;
- to ease meteoric water flow towards the Sarno River and Regi Lagni network;
- to laminate these flows before the final inflow, because both the Sarno River and the Regi Lagni network, due to the narrow river beds, are not capable to support even low-volume floods;
- to direct the debris flows towards the sites selected for their controlled inflow.

To obtain these results different kinds of engineering measures were designed and realized after 1998 in the Sarno area. Main kinds of interventions consisted in:

- Reinforcement of the possible detachment zones.
- Building of check dams along the flow streams, to prevent the erosion and stabilize the slopes as well as to reduce, at least temporarily, the slope.

- Channelisation of the flow streams to better drain both meteoric waters and debris flows.
- Building of debris flow basins and/or expansion zones at the outflow of the main gullies to facilitate the spreading of remobilized material in a safe zone.
- Building of debris barriers to divert the debris flows.
- Building of drainage channels downstream of the main mitigation measures to control the flow of meteoric waters.
- Building of water lamination basins aimed at modulating water inflows in the Sarno river and the Regi Lagni network in case of exceptional floods.

Different typologies of anthropic measures are generally combined to gain the best level of protection. Now at Sarno the hazard level of possible future debris flow events is controlled through reinforced concrete check dams and retaining walls, diverting measures, drainage channels and, most of all, three large expansion areas have been established (Curti, Episcopio and Mare), located right upstream of the center of the town, in each of which several gullies inflow. The correct drainage of meteoric waters is achieved by a net of artificial channels both crossing the expansion zones and contouring them, all converging into retention basins which, in case of an exceptional flood, should allow to reduce the water flow towards the Sarno River (Fig. 17).

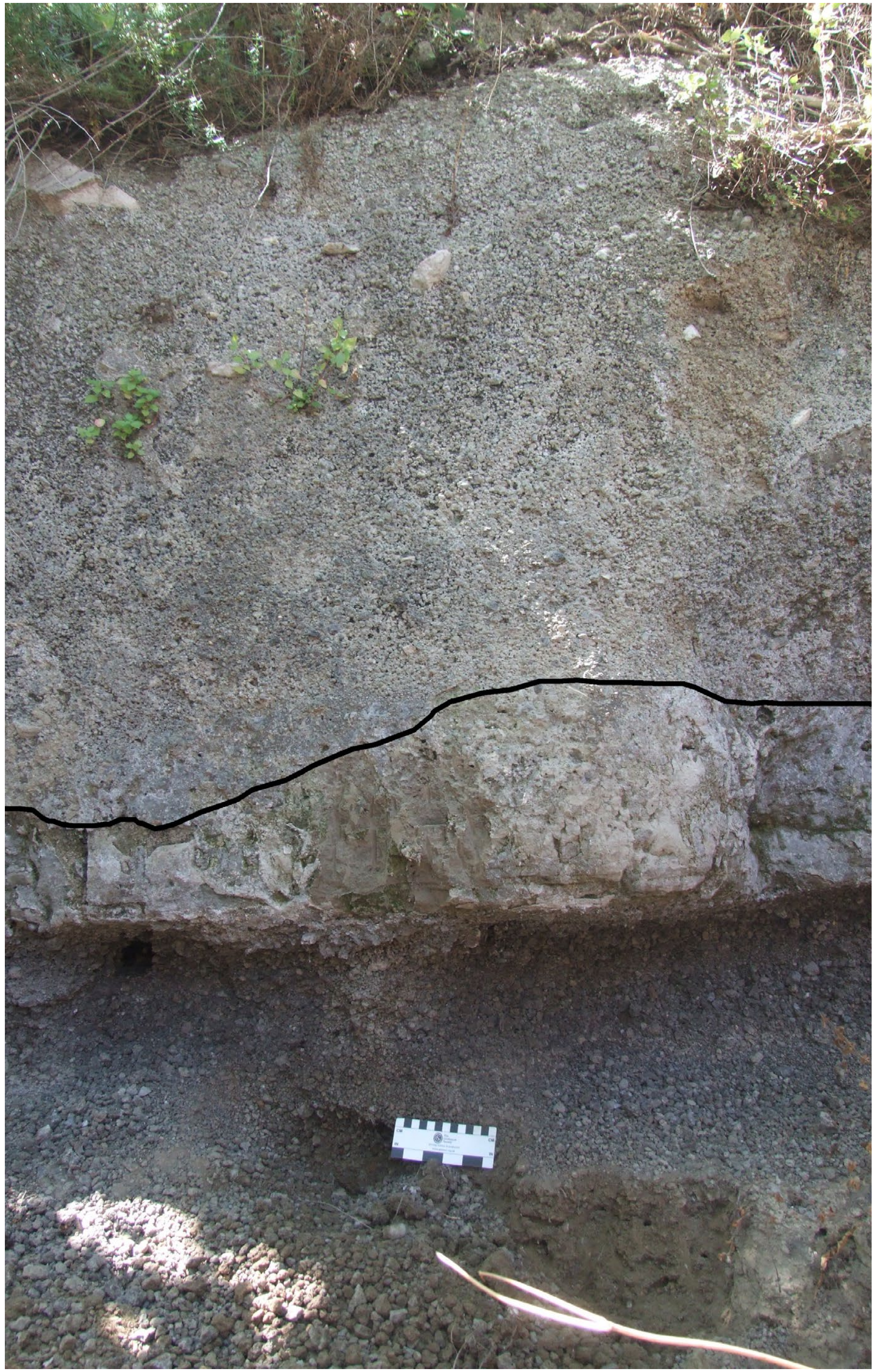

Fig. 15 - Episcopio locality (Sarno). Pumice fallout deposit of the 1631 AD eruption and the overlaying ash fallout deposit (below the black line). The upper part is composed by a sequence of syn-eruptive debris flow deposits (after Sulpizio et al., 2006).

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Fig. 16 - Episcopio locality (Sarno). Thick sequence of syn-eruptive debris flow deposits, related to the 1631 eruption.

Fig. 17 - Engineering works built after the 1998 landslides at Sarno. In the foreground, Episcopio retention basin (net capacity: 176,000 m^3), designed to collect water and debris coming from the Trave, San Chirico, Cantariello and Licinatonda sub-basins.

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Fig. 18 - Soil bioengineering techniques (live cribwalls and blankets) at Vallone Castagnitiello (Sarno).

Furthermore, soil bioengineering techniques, the main active method of stabilizing or protecting eroded soils, were also applied in some of the main landslide detachment zones in the Sarno area. Plants and plant parts (roots, stems) were used as the main structural components to reinforce the soil and to provide protection. Live cribwalls, with adequate drainage, were constructed to prevent soil sliding along track cuts (Fig. 18).

When managing hazard mitigation through engineering works, however, it is necessary to prepare a systematic mitigation plan which involves also the maintenance of these measures. To ensure the longevity of the debris flow mitigation system, during the construction, the construction quality should be inspected. After the debris flow mitigation measures are installed, their operation and maintenance, such as dredging to maintain the capacity of the dams and repairing abrasion of the drainage channel, must be performed in a timely fashion. This involves high expenses that must be yearly afforded by the local authorities. Probably because of an incorrect financial planning, both engineering risk mitigation measures and soil bioengineering works at Sarno are currently in a clear state of deterioration (Fig. 19).

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Fig. 19 - (A) Tree trunks and damp at San Vito retention basin (www.sarnonotizie.it) and (B) burnt live cribwalls (Sarno).

Stop 1.4: Nocera Inferiore – Monte Vescovado debris avalanche (470474 E, 4508911 N)

Significance: recent landslide (March 2005) – Vescovado locality. Discussion points: post-eruptive debris flows, origin and relationships with the primary pyroclastic deposits.

On March 4th 2005 a debris avalanche occurred along the slopes of Lattari Mounts (Montalbino locality) at Nocera Inferiore (province of Salerno) involving ash-fall pyroclastic deposits, mainly derived from the eruptive activity of the Somma-Vesuvius volcano and lying on a bedrock constituted of Mesozoic fractured limestones. Unfortunately, the landslide caused three casualties, as a consequence of the burial of a house located at the immediate footslope of the hill. The landslide was triggered by a heavy rainstorm occurred in the preceding hours after at least a couple of days, when slight snowfall had occurred. The landslide took place on a steep, open slope, with a slope angle varying between 30° and 40° (Fig. 20).
Figure 21 shows the succession of deposits involved in the landslide, as surveyed by De Vita et al. (2017) in the cuts exposed after the event. The main primary deposits are from the Somma-Vesuvius 79 AD and

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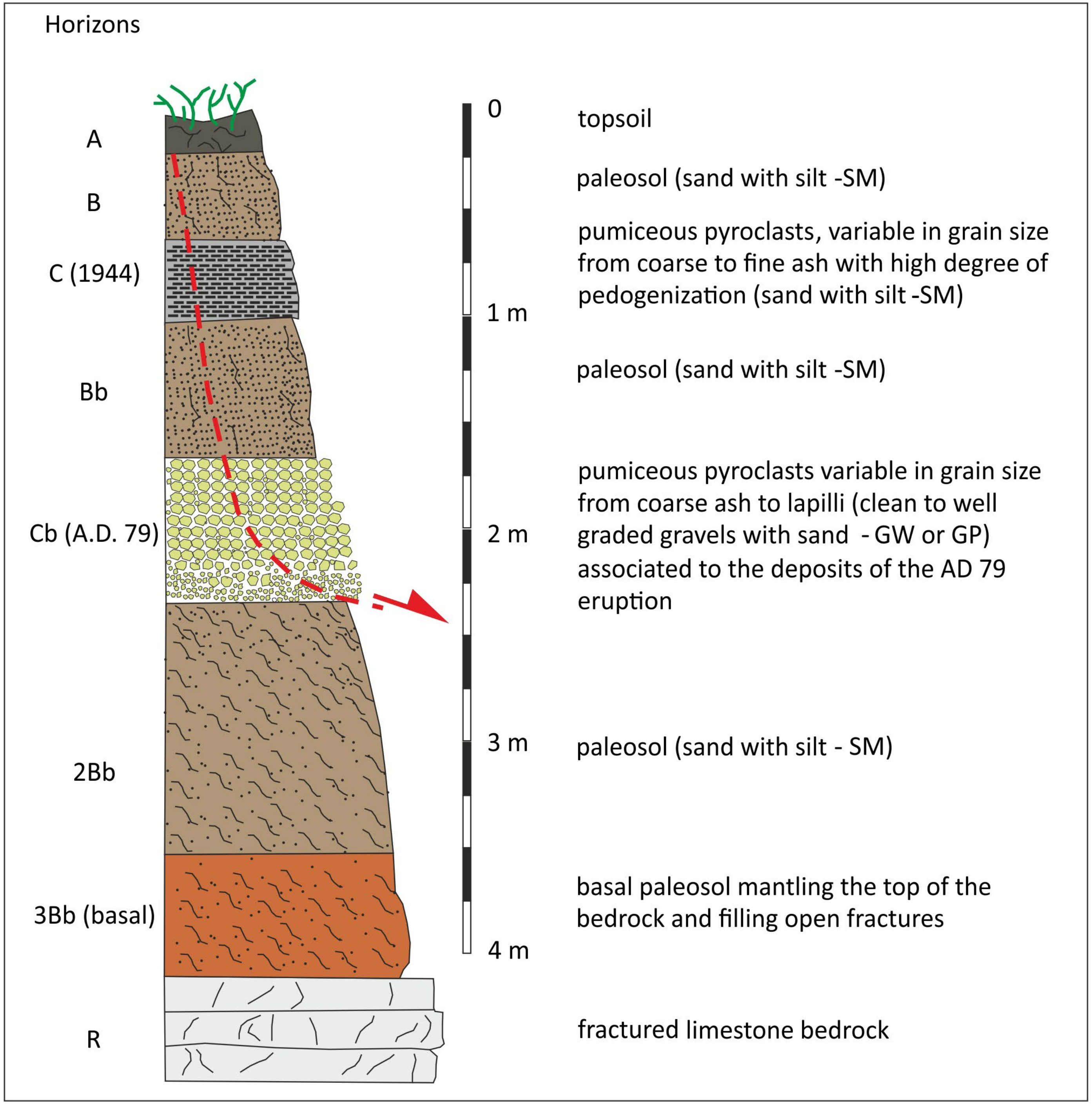
Fig. 20 - The Nocera Inferiore – Monte Vescovado debris avalanche shortly after the event. On the left a limestone quarry area. The paths of the tracks cut to reach the quarry are well evident along the slopes. From de Riso et al. (2007).

1944 eruptions, but also paleosols rich in vitric fraction, derived from the humification of ash- and lapilli-sized volcaniclastic deposits, were involved.

The observation of the stratigraphic setting along the main scarp revealed that denudation processes, among which landsliding prevailed, had already been active along the slopes, since the thickness of the pyroclastic fall and soil cover varied between 1.5 to 3.5 m, with the maximum thickness in the initiation area. In the initial slide pyroclastic horizons and soils down to the Cb horizon (79 AD eruption) were involved, and the surface of rupture corresponded to the 2Bb soil horizon (Fig. 21). In the subsequent avalanche stage, the other pyroclastic horizons were also mobilized, determining the almost complete detachment of the pyroclastic and paleosols blanket and the denudation of the limestone bedrock. The distribution of pyroclastic deposits along the slopes is a primary factor of landslide susceptibility, to be taken into account along with morphological features such as slope angle and discontinuities in the longitudinal profile of the slope, both of natural or artificial origin (Calcaterra et al., 2003b; Di Crescenzo and Santo, 2005; Guadagno et al., 2005; De Vita et al., 2013; Revellino



et al., 2013). In the Monte Vescovado landslide specific case, the trail cut a few years before the event, in order to make it possible to reach by car a limestone active quarry located nearby, possibly played an important role in triggering the sliding phenomenon.

Fig. 21 - Stratigraphic column of the ash-fall pyroclastic blanket assessed in the Nocera Inferiore - Monte Vescovado area at the top of the main scarp in a sector with a slope angle of 32°. Modified from De Vita et al. (2017).

Day 2nd: Recent landslides: from relationships between pyroclastic sequences and recent landslides to emergency management

Stop 2.1: Mugnano del Cardinale (472416 E, 4528203 N)

Significance: pyroclastic sequences of the Vesuvio eruptions along the Apennine slopes. Discussion points: emplacement mechanism, internal sequence, grain size and relationships with debris flows.

During the past 40 ka, many eruptions of Campi Flegrei and Vesuvius largely affected the Campanian Plain and the Apennine reliefs with the emplacement of thick sequences of pyroclastic deposits. These deposits are separated by variably mature paleosols generally composed of pyroclastic material. In this stop a sequence of the higher magnitude eruptions of Campi Flegrei and Vesuvius is exposed.
The lowest pyroclastic deposit is the "Campanian Ignimbrite" (40 ka; Fisher et al., 1993; Rosi et al., 1996; Giaccio et al., 2017 and references therein) and includes a thick fallout deposit (A in Fig. 22), partially covered by a recent wall, and a gray-purple tuff emplaced by PDCs (B in Fig. 22).
This tuff is overlain by a sequence of paleosols (p in Fig. 23) intercalated to the fallout deposits related to the following Plinian eruptions (Fig. 23):

- pomici di Base (Bertagnini et al., 1998);
- pomici di Mercato (C, in Fig. 22 and 23) (Mele et al., 2011 and references therein);
- Agnano-Monte Spina (de Vita et al., 1999);
- pomici di Avellino (D in Fig. 23) (Sulpizio et al., 2010b);
- pomici di Pollena (E in Fig. 23) (Sulpizio et al., 2005).

In an adjacent valley the Pollena deposits are overlain by a related sequence of thick syn-eruptive debris flow deposits containing abundant potteries of Roman time.

Stop 2.2: Quindici (470505 E, 4523034 N)

Significance and discussion point: the geomorphological features of recent debris flows (May 1998).
Vallone Connola and Vallone San Francesco cut the northern slope of Mount Pizzo D'Alvano (1133 m a.s.l.), made up of a Cretaceous to Tertiary limestone-dominated carbonate sequence. The bedrock is overlain by the pyroclastic

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fall deposits mainly ascribed to Somma-Vesuvius, even though a minor contribution of Campi Flegrei explosive activity is recorded. The geomorphological setting of Pizzo D'Alvano is controlled by tectonic and karst processes, because the very steep and rectilinear valleys which dissect the flanks mainly follow the tectonic lineations, whereas the flat surfaces, on the top of the relief and even along the slopes, reflect the effect of karst activity. The steepness of the slope is locally increased by the presence of vertical cliffs where limestone is exposed. Signs of anthropic activity are represented by the tracks cut to connect the roads at the footslope to the summit plateau. Vallone Connola and San Francesco were the pathways for huge landslides occurred on May 5th 1998 which, at the age, left them fully denudated of the hazelnut and chestnut trees that crop inside; currently, new vegetation is gaining space in the valleys and the once very evident fingerprints of the landslides are progressively vanishing.

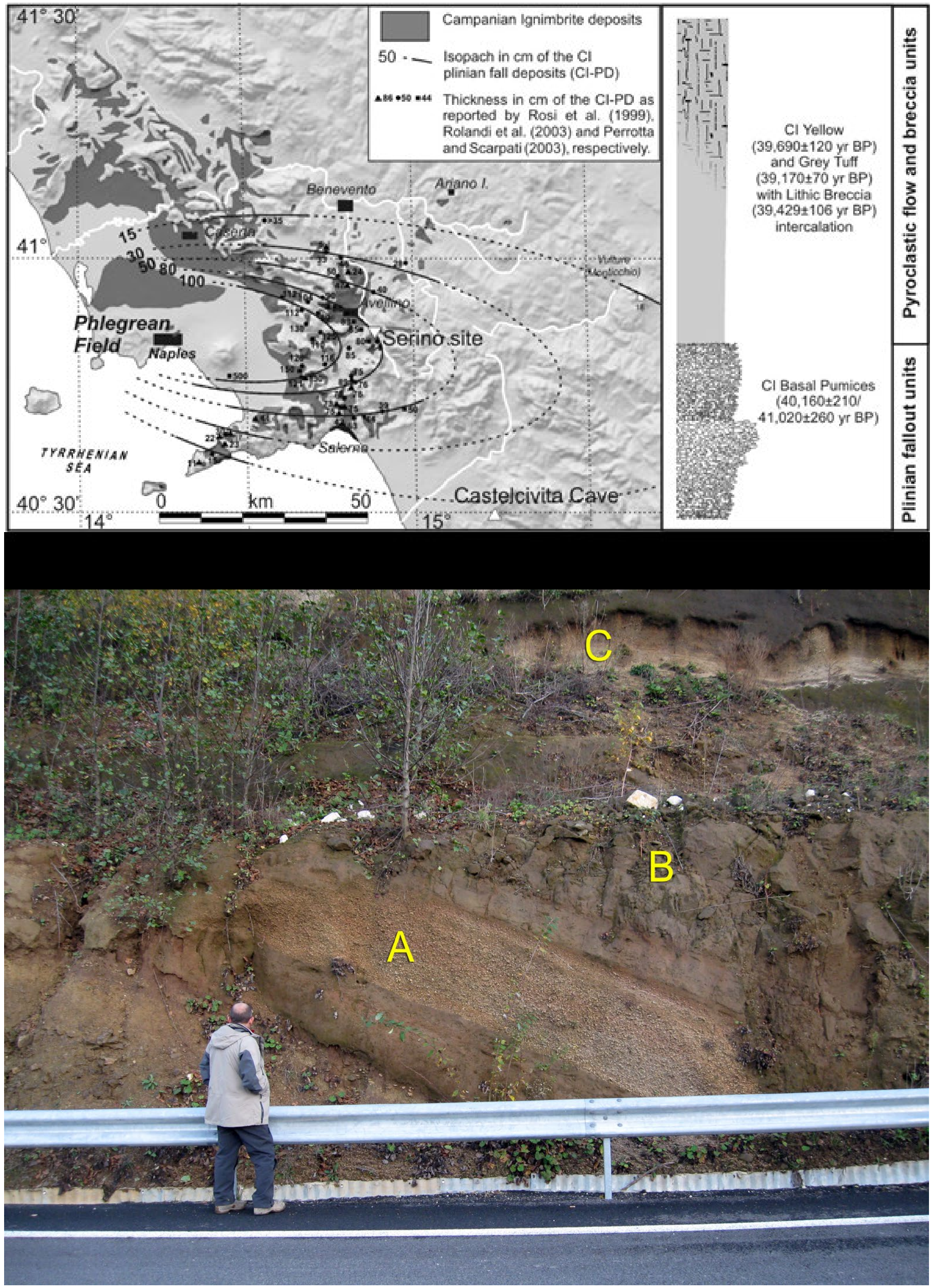

Fig. 22 - Distribution of the "Campanian Ignimbrite" intermediate-proximal deposits with superimposed isopachs of the Plinian fallout unit (details and complete references in Fedele et al., 2003, and Giaccio et al., 2008). Inset: generalised section of the "Campanian Ignimbrite" in proximal areas, with its distinctive units and related $^{40}Ar/^{39}Ar$ ages as reported by Giaccio et al. (2017). The photograph shows the deposits of the "Campanian Ignimbrite" at Monteforte Irpino (AV). The sequence overlays a paleosol and includes the "Campanian Ignimbrite" fallout (A) and PDCs deposits (B) overlain by a thick paleosoil and the pomici di Mercato (C).

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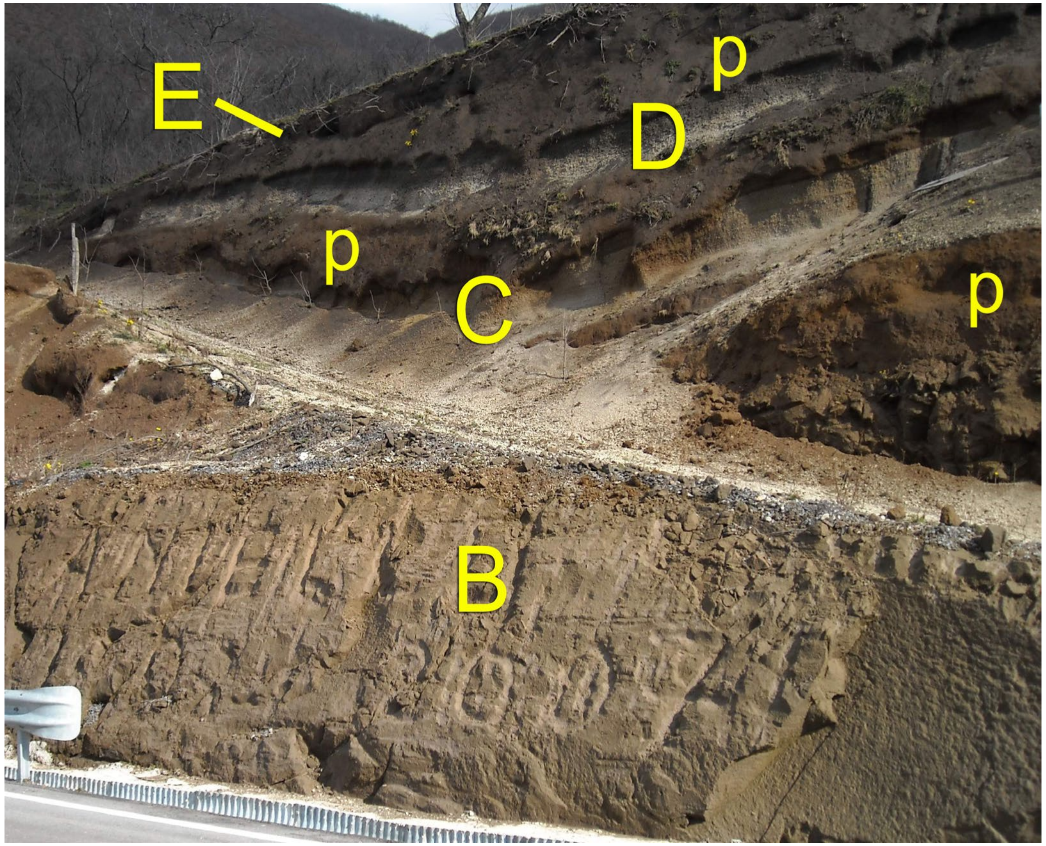

Fig. 23 - Sequence exposed at Monteforte Irpino (AV). The sequence includes paleosols (p) and from base upwards: (B) "Campanian Ignimbrite" PDCs deposits, (C) the pomici di Mercato fallout deposits, (D) the pomici di Avellino white and gray fallout deposits, (E) the Pollena 472 AD fallout deposits.

The undisturbed stratigraphic sequence of the volcaniclastic blanket in the area is reported in the description of the following stop (Piani di Prata), since primary pyroclastic deposits embedded to paleosols, in a succession up to 20 m thick, mainly outcrop in the flat areas at the top of the mountain belt, whereas reworked sediments related to gravity-driven processes prevail at lower elevation.

In the Vallone Connola - Vallone San Francesco at least 50 individual landslides were mapped rightly after the events of May 1998. The movements started as multiple (WP/WLI 1993) soil slides, and then converged into three main flows channelized inside the preexisting valley cuts, marking the passage to debris flows. Most of the initial movements started at 900 m a.s.l., even though minor events occurred at higher elevation, in correspondence of track cuts (Fig. 24).

Downslope of the detachment area, a zone with both erosion and transport is present, where removal of the pyroclastic cover remained at a very shallow level, and mainly vegetation cover was abraded with a thin layer of soil (Calcaterra et al., 2000, 2003a). The spatial extent of the erosion/transport area is wider than that of the detachment area, to testify to the high erosive power of these landslides. The mass movement in the main channels eroded the slopes of the channel, causing further instability of the pyroclastic cover and retrogressive landslides to occur. This phenomenon generally stopped when retrogressive erosion encountered a vertical limestone scarp. At Vallone Connola, very narrow and deeply incised, the transport/erosion zone is extended up to the convergence with the main valley, the so called Lagno di Quindici. At Vallone San Francesco, on the contrary, due to its progressive widening, a well-defined fan is recorded at the mouth of the valley (Calcaterra et al., 2000).

The deposition of most of the debris, however, took place only when the mass impacted the first obstacles, in the historical center of the town of Quindici, causing eleven casualties. The finest portion of the sediment kept on flowing, and was probably dispersed in the Regi Lagni, the net of channels characterizing the Campanian Plain, planned and realized in the Bourbon age.

Some trenches cut in the San Francesco fan evidenced:

- a marked lateral and vertical variation from massive and chaotic deposits to layers displaying well evident sedimentary structures (bedding, cross-lamination)
- angular limestone boulders, up to 50 cm in diameter
- a 20 cm-thick layer deposited by the May 1998 landslide event.

These features made possible to deduce that water-laid and debris-flow gravitational processes concurred along time to form the fan.

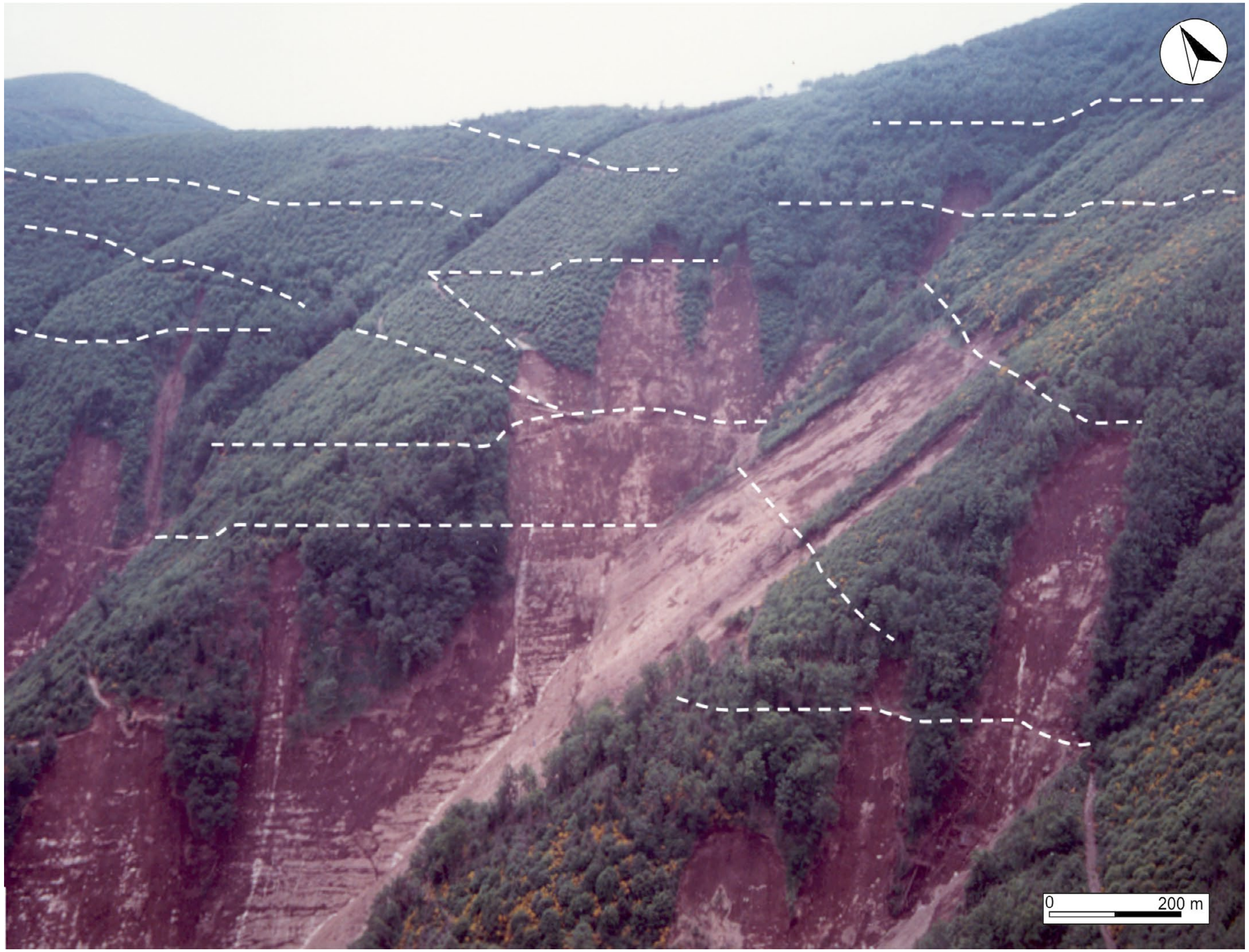

Fig. 24 - The transition soil slides-debris flows in the Vallone Connola – Vallone San Francesco area at Quindici (province of Avellino). The white dashed lines are the traces of the artificial trails cutting the slopes.

Stop 2.3: Piani di Prata (470512 E, 4520194 N)

Significance: Source areas of recent landslides and the typical highland landscape of the carbonate Apennines. Discussion points: present and past phenomena and efficiency of the risk mitigation actions.

The Pizzo d'Alvano massif is characterized by summit plains representing the remnants of an ancient tectono-karstic depression (a.k.a. *polje*), modeled during several morphogenic cycles from Late Pliocene to Late Pleistocene (Cascini et al., 2008). Piani di Prata (Fig. 25) is one of these surfaces, where natural geomorphic processes are negligible due to low slope angles and the landscape is only modified by pedogenetic processes and anthropic activities as agriculture and forestry.
Thanks to the low effects of geomorphic processes, the cuts in the summit flat surfaces, however, make it possible to observe the primary pyroclastic deposits which, embedded to paleosols, make up the succession blanketing the slopes involved by landslide phenomena.
The type section in the Piani di Prata area (Fig. 26) exposes the pyroclastic fall deposits of main E-trending Plinian and sub-Plinian eruptions of Somma-Vesuvius.

It starts with the deposits of the pomici di Base eruption (22 ka – Santacroce et al., 2008), here represented by a basal layer made up of white to greyish angular pumice fragments, 1.5 m thick, overlain by a layer of dark scoriaceous fragments, 1.5 to 2 m thick. A paleosol marks the

Fig. 25 - Piani di Prata polje at the top of the Pizzo D'Alvano limestone belt, with the detachment area of two May 1998 landslides in an oblique aerial view taken slightly after the 1998 event.

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passage to a 30 cm-thick thinly bedded layer made up of fine grained greenish to gray juvenile fragments, ascribed to the Greenish Pumice eruption (ca. 19 ka – Santacroce et al., 2008). The pyroclastic fall deposits of the Mercato eruption (Walker, 1973), also known as Ottaviano eruption (Rolandi et al., 1993), dated ca. 9 ka (Santacroce et al., 2008), follow towards the top in the type section of the area. The deposit is divided into three sublayers, mostly containing white pumice fragments covered by a yellowish patina: the basal is fine grained, the middle is coarser (diameter of clasts 1 cm) and reversely graded and the topmost is lava lithic enriched. The thickness of the whole sequence is 1 meter. Through a humified horizon the sequence passes to a 40 cm-thick layer where juvenile fragments change in color from white to gray, and lithic fragments are lava, limestone and tuffs. The grey pumice layer, 10 cm thick, sometimes is lacking. These deposits are from the Avellino Plinian eruption, dated at ca. 4.0 ka (Passariello et al., 2009). The layer is overlain by a 10 cm-thick dark horizon made up of dense scoria fragments containing leucite crystals, emplaced by the 472 AD Pollena eruption. The sequence is closed by a 20 cm-thick layer made up of angular variably vesiculated scoria fragments of the 1631 AD eruption. This sequence characterizes the Piani di Prata flat area, but the cuts along the slopes generally show mainly the primary Mercato, Avellino and 1631 AD eruption pyroclastic fall deposits, testifying that the progressive effects of intervening water- and gravity-driven denudational phases removed the deposits of the other Somma-Vesuvius explosive events (Palma et al., 2009).

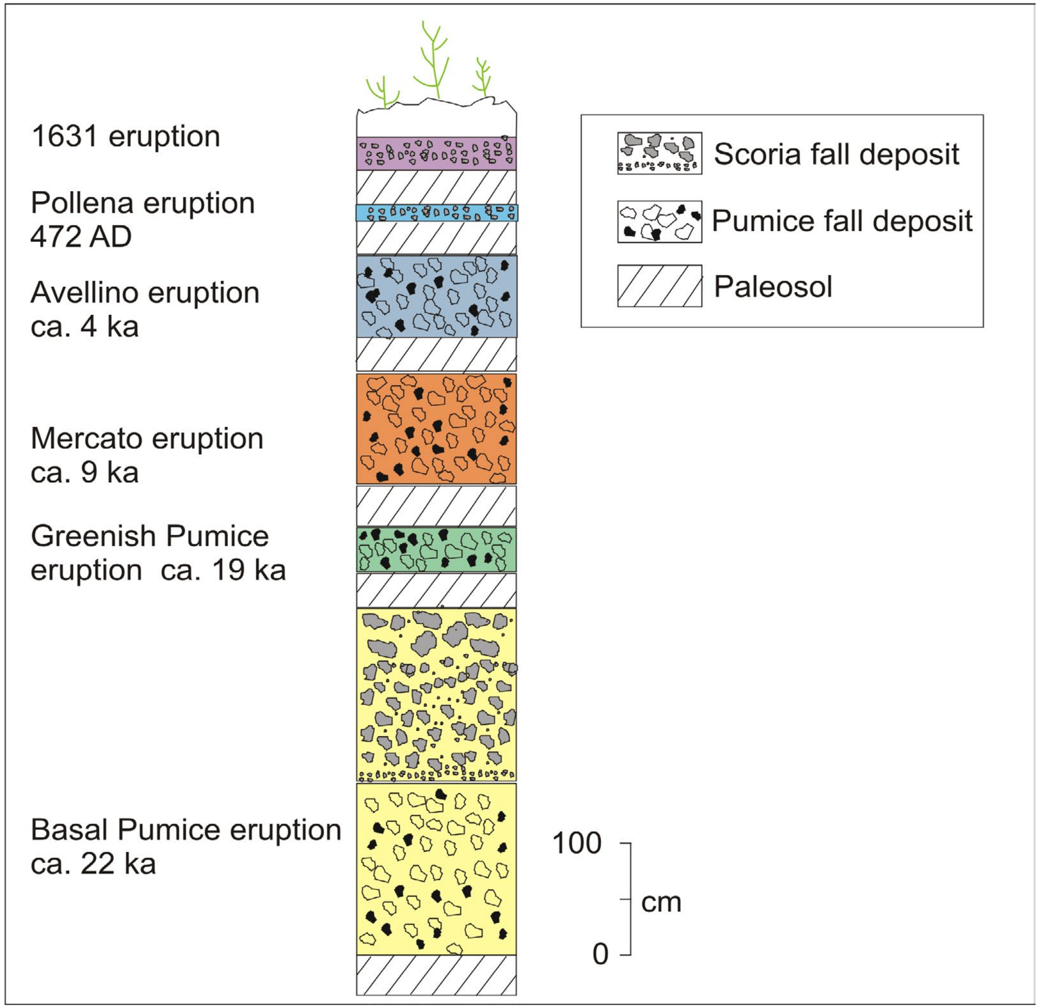

Fig. 26 – Composed type section of the Somma-Vesuvius pyroclastic fall deposits at Piani di Prata. Map of the area in Fig. 2.

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Stop 2.4: Sarno C.O.C. (467987 E, 4518205 N)

Significance: Visit to a Municipal Operative Center. Discussion points: hydraulic risk, emergency management, preparedness measures/response actions.

At the single municipality level, Italian laws, after Decree Law n. 112 of 31.3.1998, gave a clear commitment to the majors as far as emergency planning and management was concerned, in the light of the general rules stated by the single regions according to the Civil Protection's national regulations. Moreover, the Law n.100 of 12.7.2012 stated that in three months' time each municipality must prepare and adopt a municipal Emergency Plan, with the requirement to periodically up-date it and forward the new version to regional offices. When an emergency occurs on the municipal territory the major is the main authority of Civil Protection and is entrusted with emergency management involving, at first, manpower and equipment of the municipality itself. Other kind of resources (firemen, policemen) operating on the territory can be called to go to the rescue. In case of an emergency, the major is flanked by the C.O.C. (*Centro Operativo Comunale* – Municipal Operative Center), which is committed of specific supporting functions for emergency management, and groups all the different components and operative structures of the territory. The C.O.C. resides in a devoted building, whose location has to be clearly pointed out in the Emergency Plan.
The emergency management plan of Sarno and the other municipalities involved in the 1998 landslide events, when no emergency plan existed and the rescue operations where often performed by poorly organized volunteers (Fig. 27), can be considered a masterplan for other municipalities in Italy. It consists of several main phases, here briefly summarized (Versace et al., 2008b):

- regional emergency management plan, which can be updated and adapted in the light of the experience of the single municipality;
- detailed pointing out and contouring of the zones exposed to hazard;
- dense net of pluviometric monitoring;
- choice of mathematical models relating rainfall and landslides;
- commitment of an engineer who must bring into effect urgent measures for risk reduction during the event;
- institution of the Territorial Protection Committee;
- cooperation of National Civil Protection, Regional Civil Protection, COC of the single municipalities involved and, finally, Field Surveys Teams, composed of both geologists and civil engineers.

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The participants to the field trip will meet, at the C.O.C. location, some representatives of the committee for Sarno municipality and the main guidelines of the Civil Protection plan for the municipality will be illustrated, along with the single commitments and the phases of emergency management in case of possible occurrence of a landslide.

Fig. 27 - Volunteers flanking the firemen during the rescue operations at Episcopio (Sarno) (http://chiarabraga.it/tag/1998-sarno/).

Day 3rd: Deep Seated Gravitational Slope Deformations and Debris Avalanches at Ischia

Stop 3.1: Monte Nuovo, Forio, Ischia (405230 E, 4508952 N)

Significance: Monte Nuovo, deep seated rock mass deformation due to Mass Rock Creep (MRC) as a possible stage preceding rock avalanche generation. Discussion points: relationships between volcanism and related phenomena (timing, impact, characteristics).
For the detailed description of this stop see Sansivero et al., this volume, Stop n. 3.1.

Stop 3.2: Forio (405577 E, 4507764 N)

Significance: The deposits of debris/rock avalanches and lahars related to the Mt. Epomeo resurgence. Discussion points: relationships between volcanism and related phenomena (timing, impact, characteristics).
For the detailed description of this stop see Sansivero et al., this volume, Stop n. 3.2.

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