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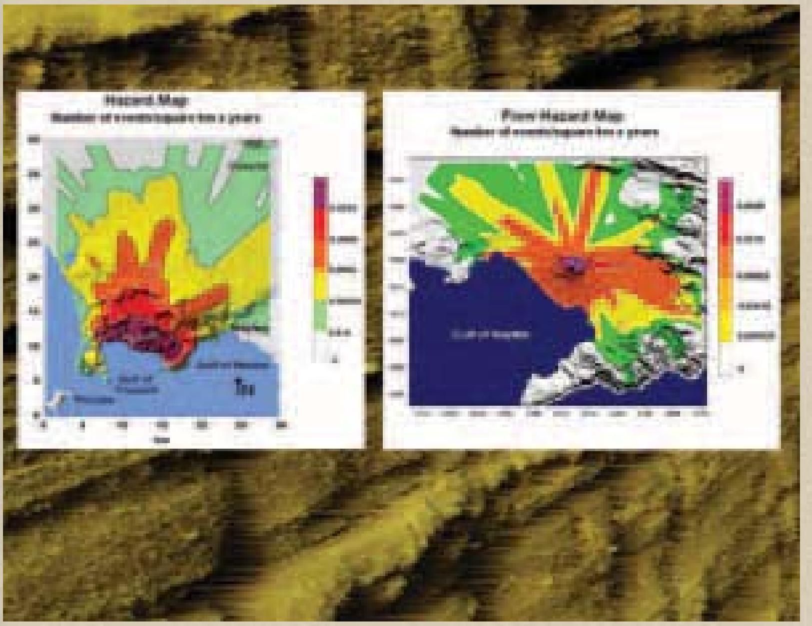
ACTIVE VOLCANISM AND RELATED EVENTS IN CAMPANIA: PRIMARY AND SECONDARY EFFECTS OF EXPLOSIVE VOLCANIC ERUPTIONS ON THE ENVIRONMENT AND PEOPLE



Leader: G. Mastrolorenzo

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Series Editors:
Luca Guerrieri, Irene Rischia and Leonello Serva (APAT, Roma)

English Desk-copy Editors:
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ACTIVE VOLCANISM AND RELATED EVENTS IN CAMPANIA: PRIMARY AND SECONDARY EFFECTS OF EXPLOSIVE VOLCANIC ERUPTIONS ON THE ENVIRONMENT AND PEOPLE

AUTHORS:
G. Mastrolorenzo[1], L. Pappalardo[1], I. Ricciardi[1], P.P. Petrone[2]

[1]Osservatorio Vesuviano - INGV Istituto Nazionale di Geofisica e Vulcanologia
[2]Università degli Studi di Napoli "Federico II" di Napoli, Museo di Antropologia

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Front Cover:
Hazard maps for pyroclastic density currents relative to Campi Flegrei by S. Rossano, G. Mastrolorenzo, G. De Natale, (2004) Jour. Volcanol. Geotherm. Res., 132,1-14 (left) and Somma-Vesuvius by G. Mastrolorenzo, S. Rossano, G. De Natale, (2004) Jour. Volcanol. Geotherm. Res., submitted (right).

Leader: G. Mastrolorenzo

Introduction

Several pieces of evidence on the relations between the geographic environment, the catastrophic events, and the human context make the Campanian region a point of reference for geo-archaeological research in the world. In the last few years, specific studies focused on the stratigraphy, eruptive mechanisms, and volcano-tectonic events, have revealed key evidence for expanding our knowledge of the eruptive phenomena and their effects on the environment, human settlements, and people. At present, a conspicuous range of geo-archaeological contexts are available and easily recognizable and allow us to understand better the effects of natural events which act with different intensities and on different time scales. In a relatively small area, including the Campanian Plains, with its surrounding coasts and mountains, some ten key sites, with well exposed sections, will allow us to summarize the volcanological history of the area in a trip lasting a few days. The itinerary also provides the opportunity to go on accurate guided visits to the principal archaeological sites in Campania, and to the museums, where findings from the paleolithic age to the medieval age are exposed. These bodies of evidence and related studies provide a direct element for an interdisciplinary approach to hazard evaluation in an active volcanic context that can also be exported to other areas.

The Campanian Plain

1.1 Geographic setting and active volcanism

The ca. 3000 km^2 wide Campanian plain, in southern Italy, is one of the Pleistocene-Holocene Italian coastal plains bordering the Tyrrhenian Sea and limited by the Apennine chain (Fig.1).

The nearly rectangular flat plain (average 30 m a.s.l), is elongated in a NW-SE direction for about 100 km, and occupies a wide, graben-like structural depression, due to a main regional extension, in turn due to the complex stress field produced by the great collision between African and Tyrrhenian plates in the Mediterranean area.

The plain is confined to its north-western border by Mt. Massico, and by the old stratovolcano Roccamonfina (1005 m a.s.l.). On the northern and eastern Campanian Plain edges, the boundaries consist of the barrier of the first ridges of the Apennine Chain. To the east and south-east lies the Monti Lattari chain (1444 m a.s.l.), which curves to the south towards the Sorrentine peninsula (Fig.2). The Island of Capri represents the extreme south-western limit of this chain, separated from the southern coast of the continent by the narrow Bocca Piccola sea channel. The western part of the plain degrades to the Tyrrhenian coast, which mostly features dunes to the north and volcanoes to the south.

The Pontine volcanic archipelago and the volcanic island of Ischia in the Neapolitan district, are the offshore westernmost boundaries of the Campanian territory, limiting the Tyrrhenian bathyal plain. The middle-southern part of the Plain features two principal orographic elements: the Campi Flegrei volcanic field west of Naples, and the Somma-Vesuvius stratovolcano, east of Naples.

Since the Late Pleistocene, the Plain has been affected by subsidence, partially compensated by alluvial sedimentation and volcanic mass transport from Campi Flegrei and Somma-Vesuvius, resulting in post-Wurmian seaward progradation.

During the last 50 ka, an intense explosive activity, with recurrent intervals in the order of 102 to 103 years, dispersed both primary and secondary pyroclastic products over an area as wide as 10,000 km^2, which includes the entire plain and the surroundings. Catastrophic volcano-tectonic events, such as caldera collapses, and bradyseismic movements of as much of tens of meters, induced important changes in the territory.

Stratigraphic studies reveal that from prehistory to the present time, both the Campi Flegrei and Somma-Vesuvius areas, including the area of Naples and the mountain reliefs, have been affected by volcano-tectonic events (subsidence, bradyseism, and rapid caldera collapse), as well as the coupled primary deposition of volcanic products and secondary deposition of volcanically induced mass flows. Selected stratigraphic sections describe the volcanological history of the area and the effects of the explosive events on the human settlements. In particular, in the last two-thousand years, tensof catastrophic landslide and flooding events have occurred. They have been recorded in the archeological stratigraphy and have often been reported in historical chronicles.

Analysis of historical reports, integrated with field recognition, and laboratory analyses, reveal that such events range over a relatively wide size interval, which includes nearly all types of phenomena induced by extreme precipitation, volcanic and seismic activity, slope instability and human modifications, which represent a significant aspect of the prevailing geolo-

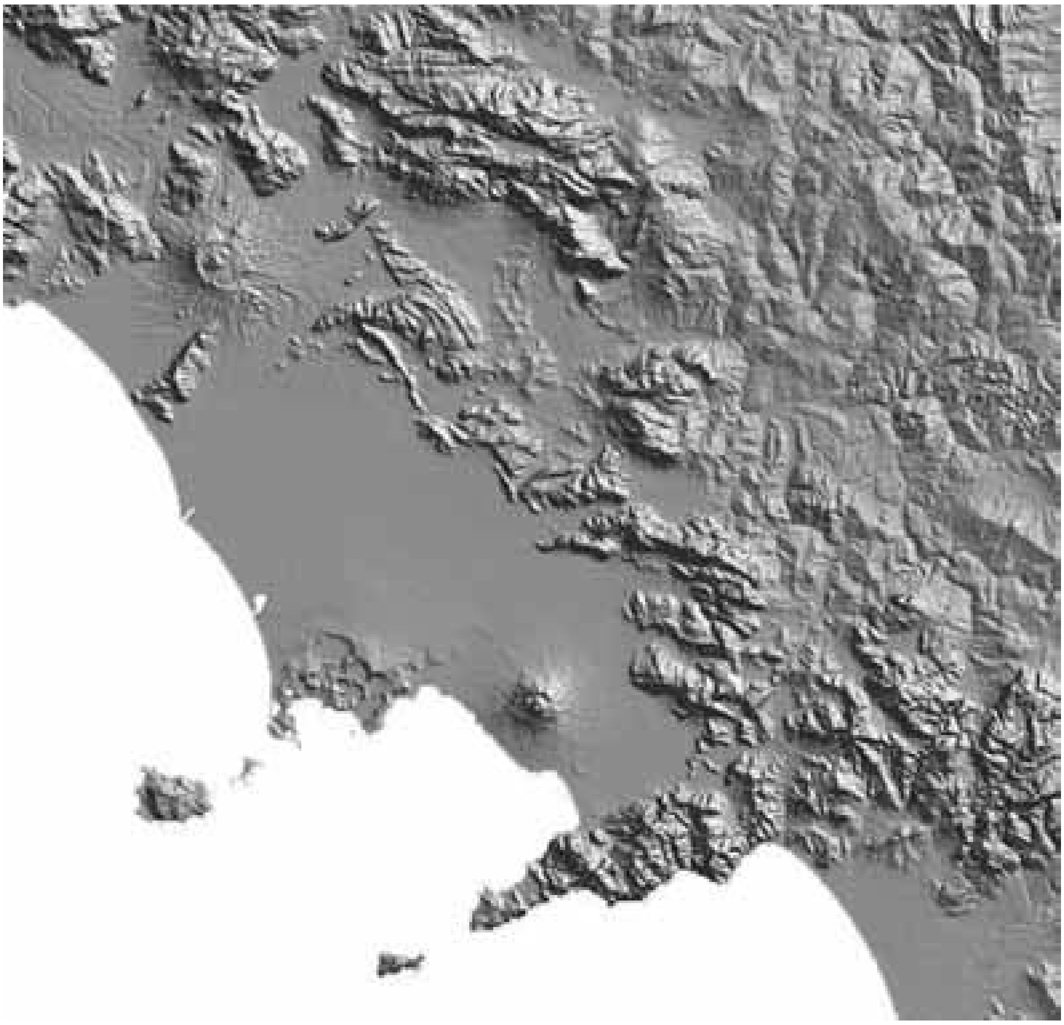


Figure 1 - Digital Elevation Model image of the Campanian Plain.

gical hazard in the Campania region.

In the following paragraphs, descriptions of the volcanic stratigraphy and striking prehistoric and historic examples of volcanic and volcanically induced events are described (Fig.3).

1.2 Magma genesis and evolution

The Campanian volcanic rocks belong to the KS series of Appleton (1972), and range in composition from shoshonite to trachy-phonolite, that are the most widespread products. At Somma-Vesuvius, mildly to highly undersaturated rocks belonging to HKS of Appleton (1972), ranging in composition from alkali-basalt to phonolite, also occur.

The source of magmatism has been located in a mantle, variably enriched in incompatible elements, radiogenic Sr and unradiogenic Nd. Debate exists about the agents of enrichment that have been identified as a) mantle-derived fluids in a intra-plate tectonic setting (e.g. Hawkesworth and Vollmer, 1979; Cundari, 1980; Vollmer, 1989) or b) fluids or melts released by an undergoing oceanic slab (e.g. Peccerillo, 2001, and references therein) which modify a OIB-type (e.g. Beccaluva et al., 1991; Peccerillo, 2001) or a MORB-type mantle (e.g. D'Antonio et al., 1996). Piochi et al., 2003, proposed two different mantle sources in the genesis of the magmas erupted in the Campanian region: a deeper asthenospheric mantle source, from which also the Tyrrhenian magmas derived, and an upper enriched lithospheric mantle source. The last contribution becomes more pronounced moving

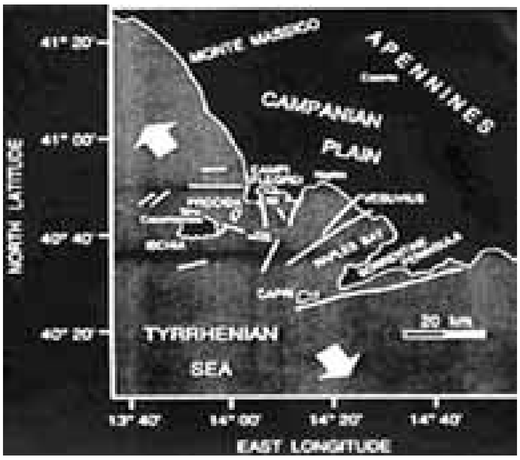


Figure 2 - Location map of Naples Bay, which lies in the southern portion of the Campanian Plain. A northeast-southwest volcanic zone, identified by three volcanic centers Campi Flegrei, Procida, and Ischia-defines the northwest boundary of Naples Bay. Hatched lines show the major normal faults identified by Finetti and Morelli (1974). Additional normal faults have been added from the geological map of Ischia (Consiglio Nazionale delle Ricerche, 1986), and from results of a detailed seismic reflection survey conducted along the undersea portion of Campi Flegrei (Pescatore and others, 1984).

from offshore volcanoes (Ischia and Procida Islands), through onto land volcanoes (Campi Flegrei and Somma-Vesuvio), likely in response to the thickening of the lithosphere observed under the Peninsula.

Major and trace elements, Sr-Nd-Pb isotope variations shown by the Campanian rocks has been attributed to complex evolutionary processes, involving magma chamber refilling, magma mixing, and crustal assimilation by mantle-derived magmas in a multi-depth magmatic system. In particular, the existence of both deep and shallower crustal reservoirs has been proposed in several studies of the Campanian volcanoes (Marianelli et al., 1999; Piochi et al., 1999; De Astis et al., 2002; Pappalardo et al., 1999, 2002). Inside the Phlegraean Volcanic District, constituted by Campi Flegrei, Procida, and Ischia, the deeper reservoir was tapped by the regional fault system during eruptions, thereby extruding the least evolved magmas that mingled during ascent with magmas evolving at shallower depth.

Figure 3 - May 5 - 6, 1998, Sarno flooding and landslides events.

The Campi Flegrei volcanic field

2.1 Geological setting and volcanological evolution

Since past centuries, the Campi Flegrei volcanic field has been one of the classical subjects of the international geological literature, and among the most famous volcanoes in the world. Even if only one eruption has been documented by eye-witnesses in historical times, since prehistory the interest for the Campi Flegrei has been stimulated by a variety of natural phenomena. These include hot springs, fumarolic exhalations in the Solfatara crater and other sites, ground movements, (bradyseism) and earthquakes.

The most conspicuous geological feature of Campi Flegrei is a 12 km wide, collapsed caldera, outlined on land by a discontinuous ring shaped hilly morphology with inward-facing scarps enclosing the volcanic field (Fig. 4).

The caldera rim, inferred in scattered points by the stratigraphic sequence (Camaldoli hill), ranges in elevation between about 450 meters and a few tens of meters, and one third of it continues below sea level, forming Pozzuoli Bay. A few submerged volcanic relicts represent the submerged part of the volcanic field. The southern limits of the caldera are poorly known and mainly inferred by the geophysical investigations. A near vertical fault system defines the geometry of the central depression, which characterizes the nearly perfectly circular caldera structure.

The intracalderic area of Campi Flegrei shows the typical features of a volcanic field characterized by different land forms. It includes closely-grouped volcanic hills, coalesced craters, depressions bordered by steep, eroded volcano flanks, and fault scarp faces, crater-filling lakes, and relicts of ancient marine terraces.

The few major intracalderic plains of Fuorigrotta, Soccavo, Pianura, S.Vito, Quarto, and

Figure 4 - Digital topographic map of the Campi Flegrei volcanic field, including monogenetic volcanoes and volcanic formations.: AS = Astroni tuff ring; AV = Averno tuff ring; BA = Baia tuff ring; BM = Breccia Museo pyroclastic flow formation; FB = Fondi di Baia cinder cone; MI = Miseno tuff ring; MN = Monte Nuovo cinder cone; MP = Montagna spaccata Strombolian formation; MS = Monte Spina small scale pyroclastic flow formation; MSA = Monte S. Angelo plinian deposit; NI = Nisida tuff cone; SF = Solfatara tuff ring; SG = Senga spatter cone; MO = Minopoli violent strombolian formation; PP = Pomici Principali Plinian formation; TGN = Neapolitan Yellow Tuff.

La Schiana, are associated with localized subsidence areas, due to local movement following eruptive episodes.

The coasts of Campi Flegrei can be grouped into two principal types: the lows are beaches at the termination of alluvial plains, and the steep, mostly tuffaceous, cliffs are natural sections of volcanic cones eroded by the sea or dislocated by faults (volcano-tectonic events). Littoral dunes and lagoons (Patria, Fusaro, Miseno, and Lucrino lakes) created by sand bars complete the beautiful physical setting of the territory.

Accurate geochronological analyses now supply an objective control on the stratigraphic correlations, and more effective constraints on the ages of the main volcano-tectonic events. The Campanian Ignimbrite and even the early caldera depression are about 39000 yr B.P. (De Vivo et al., 2001); while the subsequent largest event that generated the Neapolitan Yellow Tuff, recognized as a unique giant eruption, occurred ca. 12,000 yr B.P., and caused the several hundred meter collapse of the caldera inner part. Indeed the caldera rims, recognizable in the field and via geophysical methods, coincide with the deep dislocation in the Neapolitan Yellow Tuff formation. This evidence confirms that the ground depression, partially pre-existing the Neapolitan Yellow Tuff, was also renewed after that eruption. The intracaldera eruptive activity which occurred after this second caldera collapse, consisted of at least 60 eruptions, mostly explosive, from some tens of distinctive scattered vents (monogenetic events).

2.2 The magmatic system

The magmatic system of Campi Flegrei consisted of a large shallower magma chamber that erupted predominantly trachytic magmas in the last 100 ka. During the initial 100 – 44 ka period, trachytic magmas were erupted preferentially from vents located along NE-SW tectonic lineaments, and this first magmatic stage culminated in the formation of the caldera at about 39 ka, with the catastrophic eruption of the voluminous (150 km^3 DRE) trachytic Campanian Ignimbrite deposits. Following this eruption, magmatism continued inside the caldera rim, and was trachytic and subordinately latitic in composition. Trachybasaltic magmas were erupted only between the 12 and 8 ka period of activity, through vents located on a NE-SW regional fault system that probably tapped a deeper least-evolved reservoir.

2.3 The caldera-forming eruptions: the Campanian Ignimbrite and the Neapolitan Yellow Tuff.

The Campanian Ignimbrite is an Upper Pleistocene trachytic deposit exposed in an area within 80 km from Naples. It crops out in isolated valleys in the Apennine Mountains, Roccamonfina volcano, and the Sorrento Peninsula, and underlies much of the Campanian Plain north of Naples. Campanian flows encountered mountains at least 1000 m high to arrive at distal exposures in the Apennine valleys. Some authors relate the Campi Flegrei caldera collapse to the Campanian Ignimbrite eruption (Rosi and Sbrana, 1987; Barberi et al., 1991; Orsi et al., 1996; Rosi et al., 1996). Barberi et al. (1978) and Di Girolamo et al. (1984), suggested that the source for the Campanian Ignimbrite was a NW-SE trending fracture, north of the Campi Flegrei. Scandone et al. (1991) present evidence for a large depression of tectonic origin near Acerra, northeast of Campi Flegrei, which they suggest was a source for the Campanian Ignimbrite. This depression, and the one east of Lago Patria, are notable for having great thicknesses of Campanian Ignimbrite. The age of Campanian Ignimbrite is defined at 39 ka by De Vivo et al.(2001) on the basis of new 40Ar/39Ar data. Moreover, the products of three periods of trachytic ignimbrite volcanicm (289-246 ka; 157 ka, and 106 ka) have been identified in the Apennines by Rolandi et al.(2003). These deposits represent distal ash flow units of ignimbrite eruptions which occurred in the Campanian area in the last 300 ka.

Proximal facies: breccia deposits, which were named Museum Breccia by Johnston-Lavis (1889) occur along the slopes bordering the Campi Flegrei caldera, and on the island of Procida. These deposits have been interpreted either as proximal facies of the Campanian Ignimbrite, on the basis of stratigraphical, sedimentological, and compositional characteristics (Rosi and Sbrana, 1987; Rosi et al., 1996) or as the products of variable local eruptions (Di Girolamo et al., 1984; Perrotta and Scarpati, 1994; Melluso et al., 1995). One of the main points to support the hypothesis of many local vents, is the scattering of the age of the variable outcrops. Lirer et al. (1991), have presented 14C ages detected on paleosol samples collected at Procida and Monte di Procida, at the southwestern corner of the Campi Flegrei caldera. The ages span from 17.3 to 26.7 ka, while Deino et al. (1992), have obtained a mean age of 36.2 ka for Campanian Ignimbrite distal and breccia deposits, using the laser-fusion 40Ar/39Ar dating technique.

Distal facies: the Campanian Ignimbrite (CI) is partially to non-welded throughout its extent, but is lithified by zeolites in some localities, where it is >10 m thick. The stratigraphy and general characteristics of the CI are described in Barberi et al. (1978), and Fisher et al. (1993). It is thickest in quarries in the Volturno Plain, north of Campi Flegrei, in the valleys of the Apennine Mountains, and near the shore on the Sorrento Peninsula, across the Bay of Naples from Campi Flegrei. At about 500 km^3 bulk volume and 150 km^3 DRE (Civetta et al., 1997), it is the product of the largest eruption of the Mediterranean region in the last 200,000 years (Barberi et al., 1978), and covers an area of about 30,000 km^2. The Campanian Ignimbrite includes an eastward-dispersed, Plinian fallout deposit (e.g. Polacci et al, 2003 and references therein), overlain by ignimbrite. However Rolandi et al. (2003), proposed that the pumice fallout deposit derived from a different source, located near the Naples area. Most of the tuff was emplaced by pyroclastic flows which erupted in three major pulses, fed by magma with different compositions, that moved in variable directions and reached variable distances from the eruptive vent (Pappalardo et al., 2003). The flows are believed to have traveled in the form of a buoyant, highly expanded cloud of eruptive material which overtopped Apennine ridges higher than 1,000 m and the Roccamonfina volcano, whose top is located at 1.100 m a.s.l.. Anisotropy of Magnetic Susceptibility Measurements (AMS) flow directions show that the pyroclastic currents moved radially from the eruptive vent. Pyroclastic currents were generated by deflection of these flows, which draped themselves over the local relief, and flowed towards lower elevations (Ort et al., 2002). In contrast, computer simulations (Rossano et al, 1996), indicate that the surface distribution of Campanian Ignimbrite is consistent with a radial propagation of pyroclastic density currents, at a speed of ca 160 m/s from a vent area located north of Naples.

The Neapolitan Yellow Tuff (NYT) was produced during one of the greatest eruptions of the Campi Flegrei caldera, and is by far the largest trachytic phreatoplinian deposit known. The NYT crops out in scattered outcrops over an area of ~1,000 km^2, with a conservatively estimated volume of ~40 km^3 (DRE). It has been dated at around 12 ka (Scandone et al., 1991), and outcrops mainly in the steep relief bordering the Campi Flegrei caldera. In the caldera depression, the thickness varies between a few meters to more than 100 m, and is mostly covered by younger pyroclastic deposits. The formation is mainly hydromagmatic, and consists of two main diagenetic facies; a yellow, lithified, unwelded facies rich in zeolite, and a gray, non-lithified facies called “Pozzolana” (Scherillo, 1955). Both vertical and lateral transitions between the two facies occur, even over a few meters. The stratigraphic and sedimentological analysis of the NYT (Cole and Scarpati, 1993; Orsi et al., 1992; Wohletz et al. 1995). indicates the presence of a lower member, consisting mainly of fallout units, and an upper hydromagmatic one. The lower member is more widespread than the upper, and outcrops both inside and outside the caldera, with thicknesses varing between about 10 m close to the caldera rim, to less than 1 m in distal locations. It exibits a thin stratification of phreatoplinian fall-out and surge layers, with a prevailing fine-grained fraction. In contrast, the upper member consists of a thick, coarse-grained pyroclastic flow and surge sequence, with subsidiary fall-out units. The eruptive mechanism and the location of the vent have been controversial. Two contrasting hypotheses have been proposed: a) the products were emitted at different

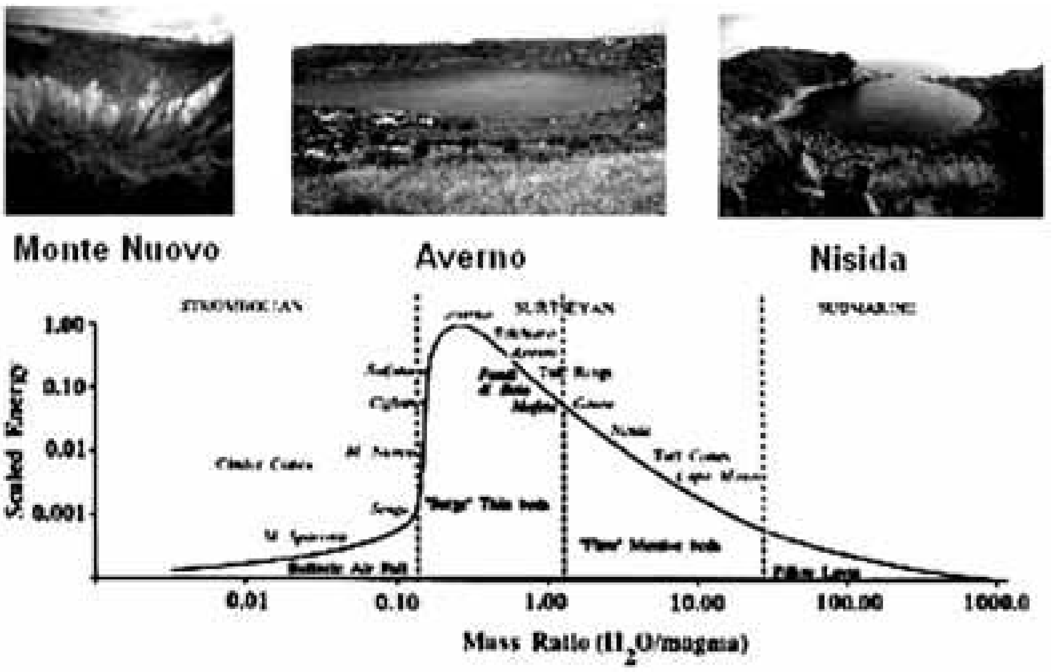


Figure 5 - Plotting of the selected hydromagmatic deposits of Campi Flegrei in the experimental diagram proposed by Wohletz (1986). The position of each formation in the efficiency diagram has been based on the grain size characteristic and the deposit features (i.e., the height to width ratio of the pyroclastic cone).

times from different eruptive centers (Parascandola 1946; Rittmann et al., 1950); and b), the formation was generated from a single huge eruption (Scherillo and Franco, 1967; Lirer and Munno, 1975; Di Girolamo et al., 1984; Lirer et al., 1987). The latter theory is strongly supported by recent detailed stratigraphical analyses. It is also supported by the anisotropy of magnetic susceptibility studies (De Gennaro et al., 1996), suggesting that the location of the vent is in the eastern part of the caldera depression. Some authors suggest that the eruption resulted in the formation of a caldera (Lirer et al., 1987) with a surface extent of 90 km^2, with a consequential down drop of approximately 600 m near its center. It is nested within an earlier caldera associated with the eruption of the Campanian Ignimbrite (Orsi et al., 1996). The NYT is composed of aphyric to subaphyric latites to alkali trachytes, with rare phenocrysts of sanidine, plagioclase, clinopyroxene, biotite, magnetite, and apatite. Mineralogical disequilibria are evidenced by xenocrysts of sanidine in latite, anorthitic plagioclase in trachyte, and alkali trachyte, reversely zoned plagioclase, and two clinopyroxenes. The composition of the erupted products reflects a complex mechanism of extraction from a chamber containing three discrete magma layers co-mingled during eruption. Pre-eruptive stratification resulted from the step-filling of the magma chamber by magma batches of variable composition. The eruption was likely to have been triggered by the arrival of new trachytic-to-latitic magma into the chamber (Orsi et al., 1992).

2.4 The recent monogenetic volcanic activity

Since the onset, the volcanism of Campi Flegrei has been mainly explosive. It includes a variety of volcanic phenomena ranging between large ignimbrites, Plinian eruptions and moderate to small scale cone-forming explosive magmatic and phreatomagmatic eruptions. Effusive activity, with associated lava flows and domes, contributes only to a small percentage of the total volume of the volcanic products. The present, intracalderic landform of Campi Flegrei is dominated by a closely grouped assortment of pyroclastic cones, ranging over the entire range of the hydromagmatic activity at shallow depth, and occurred after the emplacement of the Neapolitan Yellow Tuff. Apart from scoria cones and spatter cones, which were formed through Strombolian activity, cinder cones, tuff cones, and tuff rings result from the increasing efficiency of magma/water interaction (Di Girolamo et al, 1984;

Di Vito et al, 1985; Rosi and Sbrana, 1987; Mastrolorenzo, 1994; de'Gennaro, 1999; Mastrolorenzo et al. 2001) (Fig. 5).

About 90% of the recent caldera filling consists of pumiceous tuff and mainly unconsolidated ash, emitted in phreatomagmatic eruptions. The surface distribution of the monogenetic volcanoes reflects the tectonic and volcano-tectonic evolution of the caldera that, in turn, controlled the magma conduit position and the main ground collapses (Rosi et al, 1983).

On the basis of accurate dating and paleosoils recognition, the recent cycle of activity has been divided into two main phases: an old phase, ranging between the emplacement of the Neapolitan Yellow Tuff (ca 12,000 yrs B.P.) and about 8,000 yrs B.P., and a young phase, started about 4500 yrs B.P., and still in action. The two phases were separated by a long period of repose, which generated thick palaeosoils. Near the end of this interval, major volcano tectonic events caused the uplift of a central caldera block (Cinque et al, 1985). This event is recorded in the marine terrace, La Starza. This is a ca. 5 km long cliff parallel to the northern coastline of Pozzuoli, formed by alternate pyroclastic and marine deposits that record three separate transgressions of the sea, which occurred between 8,400 and 4,000 years ago. Absolute dating of the different deposits indicates that the uppermost marine layer was uplifted at least 40 m in less than 3000 years. The uplift was possibly due to a magma injection that announced a new intense eruptive phase.

During the early phase, the eruptions occurred from different vents located on the western and central eastern caldera sectors (Rosi et al, 1987; Lirer et al, 1987). Near the end, the activity migrated toward the center of the caldera and the Plinian deposit of the Pomici Principali was erupted from the Agnano area (age ca. 10,000 years), as well as those of Baia and Fondi di Baia (8,400 years B.P.). The volcanic activity of the latest phase is not regularly distributed both in time and space, since most of the eruptions are clustered between 4,400 and 3700 years B.P. The eruptions occurred from vents located both in the central and western parts of the caldera. A special concentration of explosive eruptions occurred around the center of the caldera. Cigliano, Mt. Spina (4,500 yrs B.P.), Solfatara, Monte Olibano, Astroni, Senga, Averno (3,700 yrs B.P.); and Monte Nuovo formations, all younger than 4,500 yrs B.P., lie within a distance of 4 km from Pozzuoli town (Lirer et al, 1987, and Rosi and Sbrana, 1987). Moreover, a particular alignment of volcanoes along a NNW-SSE direction in the western part of Campi Flegrei (Miseno, Porto Miseno, Bacoli, Fondi di Baia, Baia, Averno, and the submerged volcanoes of Bank of Miseno, and Penta Palummo) agree with the seismic profiles, indicating a possible, major recent intracalderic tectonic structure.

Other volcanic formations and edifices that were formed after the emplacement of the Neapolitan Yellow Tuff, result from eruptions that range in size and explosivity between those of Mt. Nuovo and Mt. Astroni (0.02 km^3 to 0.5 km^3). Moreover, a least three, subplinian and Plinian eruptions formed pyroclastic sheets not directly related to a specific cone (Lirer et al, 1987). Some small scale pyroclastic flows are both included in more complex cone-forming sequences, and sometimes were erupted as a prevalent part of an eruption that filled valley and cone depressions. Strongly subordinate lava flows were erupted also from vents located near the caldera center (Monte Olibano, Accademia near Pozzuoli, La Caprara, and the Rotondella in the Astroni complex).

The pyroclastic cones of Campi Flegrei represent more than 90% of the total volcanic formation in the last 12,000 years. Usually they reach 100 to 200 meters in height. However the rim of the great Mt. Barbaro tuff cone, in the middle part of the caldera, is about 340 m high. The basal diameter of the cones ranges between less than 1 km and about 3 km, while the craters range in diameter between less than 500 m and about 1.5 km.

2.5 The last eruptions (from Bronze to Modern age)

From ancient Bronze to the Modern age, an intense monogenetic explosive and subordinate effusive activity took place from vents located within the central part of the caldera (Fig. 6).

Solfatara, Astroni, Averno, and Monte Nuovo pyroclastic cones, Agnano and Monte Spina Plinian to phreatomagmatic eruptions, and Monte Olibano and Accademia lava domes are the principal events that modified the inner part of the volcanic field, and affected the human context from prehistoric to historical times.

2.5.1 The Averno eruption

The tuff ring of Averno, located about 4 km Northeast of Pozzuoli, was formed ca.3,700 years B.P. It is a wide, lake-filled volcano (Fig. 7). The crater rim is about 1000 m across, and the maximum rim elevation is ca.100 m. It has been classified as a maar type of

Figure 6 - Aerial photograph of the western part of the Campi Flegrei volcanic field, including the Averno tuff ring, Monte Nuovo, the coast of Baia, Cuma, and the Fusaro lagoon.

hydromagmatic cone, because the violence of the explosions carved a deep crater in the pre-existing yellow tuff basement (Mastrolorenzo, 1994).

The products of this eruption covered an area as wide as 50 km^2. The total volume of its pyroclastic deposits is ca.300 million cubic meters (Mastrolorenzo, 1994). Detailed petrochemical analysis of Averno pyroclastic products show a regular compositional stratification from basal peralkaline trachyte to upper alkali trachyte. This evidence suggests that the eruption was fed by a local, narrow, apical part of the magma chamber. Detailed morphoscopic analysis, by using Scanning Electron Microscopy (SEM) of small ash particles, furnishes small scale evidence that confirms the mechanisms that are assumed to have taken place in the conduit. A detailed comparative study of tens of different pyroclastic deposits (Mastrolorenzo et al, 2001), indicates that the magma-water contact mainly occurred after the gas exolution in the conduit, and frequently after the magma fragmentation into lapilli and ash. So the hydromagmatic activity took place on a simple Strombolian background style, which was related to the rising of localized and relatively small magma dykes, whose ascent was controlled by the local stress field in the middle caldera area. These pieces of evidence confirm the relevance of the coupling between the intracalderic hydrogeological setting, and the structural weaknesses. It is the nature of such a coupling that determined the eruptive style and, hence the type of volcanoes that occur.

This inferred complexity of the eruptive processes in an active caldera are confirmed by the still unsolved relation between the volcanic activity, seismic events, and ground deformation that characterize the Campi Flegrei district.

Figure 7 - The so-called Apollo Temple in the eastern lower side of the tuff ring, bordered by the flank of the older Gauro tuff cone, and the younger Monte Nuovo pyroclastic cone.

2.5.2 The Monte Nuovo eruption

The last eruption started on 29 September 1538, and in one week resulted in the formation of Monte Nuovo, 3 km west of Pozzuoli. It is the only historical eruption of Campi Flegrei (Fig. 8).

From contemporary accounts (Fig. 9), it has been possible to reconstruct the main phases of activity (Da Toledo, 1538, Delli Falconi,

Figure 8 - The Monte Nuovo pyroclastic cone.

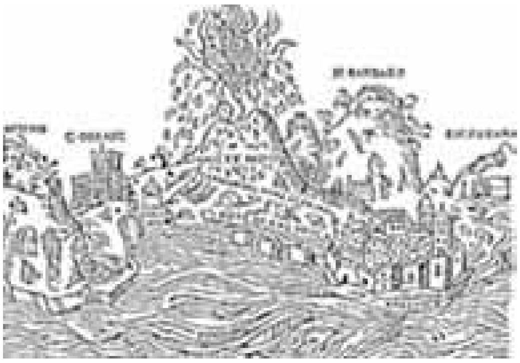


Figure 9 - Woodcut engraving that depicts the September 1538 eruption of Monte Nuovo (MOTE NOVO). This engraving accompanied the publication of the eyewitness account of the eruption, written by da Toledo (1539), published in Naples by Giovanni Sultzbach on January 22, 1539, Baia.

1538, Di Vito et al, 1987; Lirer et al, 1987; Marchesiono, 1538, Parascandola, 1943, 1946; Simone Porzio, 1551). The eruption concluded a period of local ground uplift which started a few tens of years before. A further rapid uplift, in the vent area, occurred two days before the eruption, and was observed by the inhabitants of Pozzuoli. The first two days of the eruption were characterized by moderate energy hydromagmatic activity, and led to the growth of the main body of the cone around the vent. After four days of relative quiescence, interrupted by explosions of Strombolian type, a last phase concluded the eruption with the emplacement of a directional, small-scale pyroclastic flow deposit. Field evidence indicates that the style of activity varied significantly over short periods of time, from hydromagmatic to magmatic. This fact suggests that the main factor governing the eruption was the interaction of rising magma and water. The final stage of the eruption possibly testifies the temporary exhaustion of the water reservoirs (Di Vito et al, 1987).

Nevertheless, according to the contemporary chronicles, at least 24 people were killed by the last phase of the eruption. The town of Pozzuoli, evacuated by the inhabitants, suffered severe damage both because of the seismicity and because of the eruption. The village of Tripergole was buried under the products of the eruption. Tile fragments interbedded in the pyroclastic deposits testify to this catastrophe.

Even though it was completely explosive, the eruption of Monte Nuovo was actually a relatively minor event, both in terms of its violence and the total erupted volume (about 20 million cubic meters of magma involved).

2.6 The ground movements: bradyseism and related earthquakes

The bradyseism, a slow ground movement, is the most intriguing phenomenon in Campi Flegrei.

The peculiar geographic condition of the caldera, partially submerged, represents a reference level for relative ground movements in an active volcanic area. Marine deposits, tracks of uplift or subsidence of Roman ruins, and historical documents, provide a more than 2,000 years long record of local relative sea level changes (Dvorak and Mastrolorenzo, 1991). Among the several known Roman coastal ruins, the most studied is the Roman marketplace in Pozzuoli, also called Serapis (Fig. 10). Marine molluscs, lithodomus lithophagus, have bored into it and left shells into its three standing marble columns, recording ancient relative sea level changes. The monument has been the object of much research, beginning shortly after its excavation in 1750 (Niccolini 1839, 1845; Parascandola, 1947).

However ground movements interest a wider area, including the entire caldera. Geological, oceanographic, and archaeological research has been integrated to outline a better temporal and spatial description of the bradyseism. Furthermore, since the past century, investigations of the possible causes of the phenomena have been carried out by a number of scientists. Breislak (1792) firstly suggested that the perforations and marine shells resulted from changes in relative sea level at Roman Age sites along the shoreline of Pozzuoli Bay. He further suggested that this change was due to a ground displacement associated with two earthquakes: the first earthquake lowered the monument, and the second uplifted it to the present position. Forbes (1829), Babbage (1847), and Lyell (1872) also considered the phenomena as the result of a vertical movement of the land. Both Babbage and Lyell associated the ground movement to cooling and heating processes. A different thesis was published by Niccolini (1845), and Gunther (1903) ,who explained the relative movement with a world-wide change in sea level. Parascandola, midway through the 20th century, carried out detailed analysis of the bradyseism, and in particular, of the rapid uplift recorded during the eruption of Monte Nuovo in 1538 A.D. He collected several pieces of evidence for vertical crustal movement, and outlined the history of bradyseism along the coastline of Pozzuoli Bay and the city of Naples since Roman times.

Figure 10 - Roman Marketplace in Pozzuoli: Serapis Temple

Oliveri del Castillo and Quagliariello (1969) published the first modern physical model for the bradyseism. According to their model, the rapid uplift that preceded the eruption of Monte Nuovo was due to the sudden heating and expansion of ground water. On the contrary, the subsidence has been caused possibly by self-compaction of the porous deposits filling the caldera. A different model was proposed by Neapolitan researchers in the second half of the 1970s (Corrado et al., 1977). Following a previous model by Mogi (1958), they considered the ground movement as a direct consequence of a magma pressure increase within a shallow magma chamber. A new impulse to the research was associated with a second historical period of uplift. Two distinct episodes of bradyseism occurred from 1969 to 1972, and from mid-1982 to December 1984 (Barberi et al., 1984). The beginning of the first phase was recognized by the inhabitants of Pozzuoli who noticed the offset of walls, and the raising of a bridge and wharf. The total ground uplift was about 170 cm. The pattern of the ground deformation was a nearly circular lens, with the center near Pozzuoli. However, only a weak seismic activity was recorded during this phase. The second crisis presented a similar uplift pattern. In contrast with the previous one, this episode was accompanied by intense earthquakes (Dvorak and Gasparini, 1991). Shallow earthquakes hypocenters (depth from 1 to 4 km) occurred from mid-1983 to December 1984, and resulted in structural damage in Pozzuoli. A magnitude 4 earthquake with its epicenter in Pozzuoli, occurred on October 4, 1983. The town was evacuated, and about 40,000 people were transferred. The maximum seismic energy was released in the period March-April 1984, and a succession of 550 earthquakes was recorded on April 1st. The total uplift recorded between January 1982 and December 1984 amounted to 180 cm. The raised area

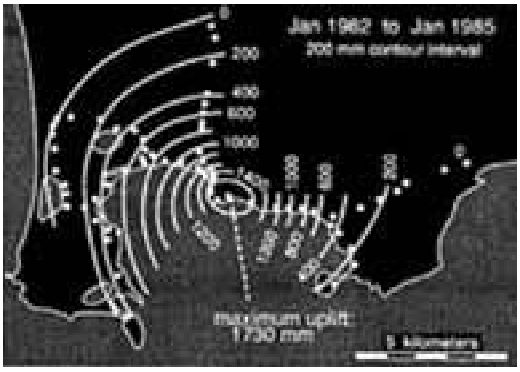


Figure 11 - Results of levelling surveys conducted between January 1982 and January 1985.
The isolines of ground deformation are in mm (Dvorak and Mastrolorenzo, 1991).

was circular and had a radius of about 6 km, again centered on Pozzuoli town (Fig. 11).

A number of scientists are involved in research on the dynamic of ground movements and additional data have been collected about the evolution of the phenomena (Luongo et al, 1991).

Results of recent research have given new likelihood to the model which is based on the thermal expansion of water-saturated deposit filling the caldera depression (Bonafede, 1991; De Natale et al, 1991; Gaeta et al.; 1998; Castagnolo et al., 2001; Troise et al., 2001). Moreover, De Natale et al., 1993, 1997, and Troise et al., 1997, have recognized and modeled the main structural effects, which explain most of the peculiar features of the Campi Flegrei unrest.

In particular, Gaeta et al. (1998) have developed a model for describing water flow in a porous medium under the effect of thermal and pressure gradients, by using experimentally-determined fluid-dynamical parameters for caldera rocks. The model simulates geothermal system in calderas, thus indicating that the water flow in shallow aquifers, under the effect of pressure and/or temperature variations within the geothermal system, can be very important in the genesis and evolution of unrest crises, and in particular, that the water flow can strongly amplify the effect of pressure increase in the magma chamber on ground uplift. The cylindrical model, with constant overpressure of the order of 10Mpa, can fit both the magnitude and the shape of the observed total uplift.

Eruptions, due to their amplitude and recurrence, together with ground movements and seismic activity, have not only greatly influenced human activity in the past, but have recently presented great problems. Their understanding and forecasting is a major task for volcanological research in Italy.

The Somma-Vesuvius strato-volcano

3.1 Volcanological setting

Somma-Vesuvius is emplaced on a regional NE-SW-trending fault system, related to the stretching of the lithosphere. It is a composite strato-volcano, consisting of the old edifice of Monte Somma, featuring a summit caldera structure, occupied in its center by the younger Vesuvius cone. Only the northern rim of the Somma volcano relict is well preserved (with a maximum elevation of ca 1130 m), and its southern rim is lowered probably because of multiple caldera collapses, as well as flank collapse, and is buried under younger volcanic deposits.

The activity of the Somma strato-volcano ended with the caldera-forming event about 17,000 years BP. The following activity was mainly located within the summit caldera, at an elevation exceeding ca 500 m asl, and only subordinately at a lower elevation on the southern slopes of the volcano. K-Ar dating of the Monte Somma lavas indicates an age between 20,000 and 30,000 years, consistent with the age of the first pyroclastic deposit (Codola formation), dated at about 25,000 yr BP. At least seven Plinian eruptions occurred after the Codola event, 22,500 yr BP (Sarno), 17,000 yr BP (Basal Pumices), 15,500 yr BP (Greenish Pumices), 11,400 yr BP (Lagno Amendolare), 7,900 yr BP (Mercato Pumices), 3,550 yr BP (Avellino Pumices) and 79 AD (Pompei Pumices) (Fig. 12).

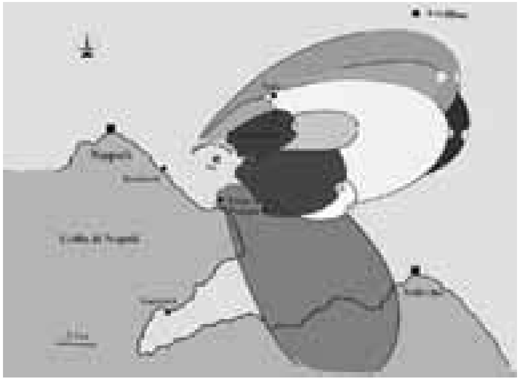


Figure 12 - Isopachs map of Somma Vesuvius plinian, subplinian, and vulcanian eruptions.

The Plinian formations of Somma-Vesuvius include fall out units mainly dispersed east of the volcano, due to the prevailing direction of the upper stratosphere and throposphere winds, as well as pyroclastic flow and surge units emplaced on the volcano flanks and the surrounding plains, up to a distance of ca 15 km from the vent (Fig. 13).

According to Delibrias et al. (1979), the Plinian eruptions in the last 17,000 years, which occurred after centuries to thousands of years of quiescence, represent the beginning event of eruptive cycles.

The last cycle started with the 79 AD eruption, and continued up to the 1944 eruption. The absence of lava flows interbedded within the pyroclastic sequences younger than 17,000 on the northern Somma slope, is the only evidence for a main caldera collapse dating at 17,000 yr BP.

The interplinian activity of the past cycles is poorly

Figure 13 - Sequence of plinian deposits of Somma - Vesuvius in S. Gennaro Vesuviano NE of Vesuvius.

known, due to the scarce surface diffusion of the product, related to moderate and small scale eruptions. Major strombolian deposits are well-documented in the stratigraphy between the Avellino and Pompei Plinian eruptions, as well as after the 79 AD, 472 AD, and 1631 AD eruptions. Detailed data available for the last cycle (79 AD to 1944 AD), indicate that the activity has been both effusive and explosive, with magnitudes of the single events ranging between a few million cubic meters, and some hundreds of million of cubic meter. Mixed effusive-explosive activity is well-documented, in particular in the paroxismal eruptions which occurred at the end of the tens of short eruptive cycles that followed the 1631 subplinian eruption, up to March of 1944.

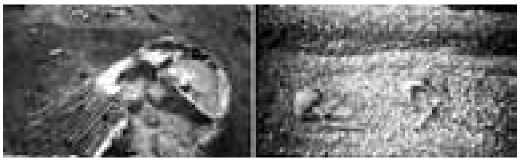


Figure 14 - Partially-preserved structure of a Bronze Age village and skeletons of human victims recovered in the Avellino Pumices deposits in the Nola district.

In 1995, on the bases of volcanological and magmatological studies, the Italian Government adopted an Emergency Management Plan for the Somma Vesuvius area, based on the scenario of the 1631 subplinian eruption.

This plan includes a possible evacuation of ca 600,000 people from the 18 towns, in the case of a future eruption.

3.2 The magmatic system

The magmatic system of Somma-Vesuvius produced silica undersaturated potassic (KS) to ultrapotassic (HKS) rocks, and consisted of multi-depth reservoirs located at about 4 and 10 km, as deduced by fluid and glass inclusion data (e.g. Belkin et al., 1998; Cioni et al., 1998; Marianelli et al., 1999). K-basaltic to K-trachytic magmas were erupted in the oldest period of volcanism, before 11,500 years BP. Between 11.5 ka BP and 79 AD, the eruptions were fed by K-tephritic to K-phonolitic magmas. Finally, between 472 AD and 1944 AD, leucitic-tephritic to leucitic-phonolitic magmas were erupted. On the basis of Sr-isotopic variations through time Pappalardo et al., 2003, hypothesizes that the eruptive events of the last period of activity (after 1805 until 1944), were fed directly by the deeper reservoir.

3.3 The last devastating events

3.3.0 The Avellino Plinian eruption (3550 yr BP): a Bronze age catastrophe

The Avellino Plinian eruption marks the boundary between the Old and Intermediate Bronze Age in Campania. Several archaeological findings, discovered in the last decades, demonstrate the strong impact of this eruption on human settlements (Livadie et al., 1998) (Fig. 14). The eruptive sequence recognized in a 180° wide sector (from West to East), north of the volcano, consist of a lower lapilli fall, and upper pyroclastic flows and surge units.

A type section of the Avellino Pumices formation identified in S.Anastasia, at Lagno Trocchia, on the NW flank of Somma, includes from the base to the top:

- thinly-stratified, massive fine ash beds (1s, 2s) and fine white pumice lapilli beds (1s).
- a 1.2 m thick massive, gray pumice lapilli layer (3f), with an underlying thin white pumice bed (2f);
- a consolidated ash layer (3s);
- a 1.2 m thick bed of massive, well-sorted ash with

accretionary lapilli (4s) with a laminated bed in its upper part (4s');
- an interstratified sequence of wavy, laminated, fine-grained ash and fine lapilli beds (5s, 6s, 7s, 8s), and massive coarse, gray pumice lapilli fallout layers (4f, 5f, 6f, 7f), 10 to 40 cm thick.

The dispersion axes of the main fallout units are oriented NNE consistently with the deposits of the other Plinian eruption of Somma-Vesuvio, thus indicating the effect of the prevailing direction of the winds from the western sectors. The dispersion and the inferred column heights of the two major Plinian deposits (2f and 3f), are 800 and 1500 km^2, and 25 and 36 km, respectively. The pyroclastic density currents (pyroclastic flows and surges) deposits are mostly diffused from NNW to NNE of the volcano, over a 500 km^2 inferred area, with a volume of ca. 1 km^3. The pyroclastic surge and flows sequence, with a maximum thickness of about 15 m (on the western volcano slope), has been recognized up to a distance of ca. 22 km from the vent. The coincidence of the surface distribution of the surge deposits with the present urban area of Naples, indicates the relevance of such types of eruptions in terms of volcanic hazard. In the last decade, a number of sites buried by the primary and secondary products related to this event have been found in the Nola plain and in the surrounding topographic hills. In particular, the partially preserved structure of Bronze Age villages have been found in Nola district, and the first two skeletons of the human victims of this eruption have been found in S.Paolo Belsito, within the fallout lapilli unit.

3.3.1 The 79 AD Pompeii eruption: the first chronicle of a Plinian event

The study of the 79 AD Vesuvius eruption, and the merging of theoretical considerations and field evidence, are critical for mitigation of volcanic disasters at Vesuvius and other explosive volcanoes.

Volcanological study, consistent with the written report by Plinius (Pliny the Younger), indicates that the Plinian eruption started around mid-day on the 24 August, with a sustained eruption column, lasting for 19 hours, which rapidly rose to an elevation of 15 km, and continued to grow to a maximum height of 32 km. Ash and lapilli, dispersed SSE of the volcano by the dominant winds, covered the land with up to a meter thick pyroclastic blanket, that partially buried Pompeii, Stabia, and several Roman villas.

At least six times in its later phase, the Plinian eruptive column collapsed, generating pyroclastic flows and surges, that spread mostly over the southern and southwestern slopes of the volcano as gravity-driven currents, thus devastating a wide area.

The first column collapse, ca. 12 hours after the beginning of the Plinian phase, formed a surge (S1) which overran the town of Herculaneum, and caused hundreds of deaths. The spreading and deposition of the surges and flows were strongly controlled by the topographic setting of Herculaneum.

3.3.2 Herculaneum: an impressive record

The town was located ca. 6 kilometers WSW from the crater, at the foot of the volcano's slope, on a dipping tuff terrace overhanging the sea, and between two

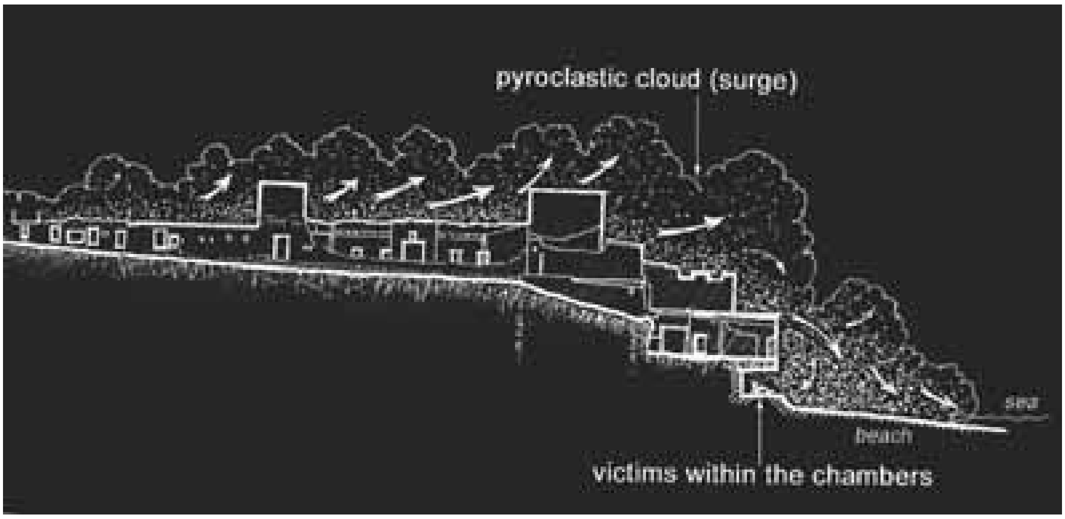


Figure 15 - Sketch of the passage and emplacement of the first surge on the waterfront area.

Figure 16 - Skeletons of human victims recovered in the chambers at Herculaneum.

rivers.

The basal pyroclastic sequence at Herculaneum comprises the deposits of the first two surges (S1 and S2) and the related flows, which formed a 2 to 5 m tuff deposit on the waterfront area. A sequence of four coupled units covers the basal units for a total thickness of 20 m. The first surge (S1) consists of a near continuous, fine-grained, massive ash bed emplaced with a thickness ranging between 0.2 and 1 m, due to the deflation of a turbulent cloud. Low angle internal laminations and pumice lenses appear only locally.

The lack of structural damage, due to the passage of the first surge (S1), indicates that it was characterized by a relatively low momentum and low carrying capability, in contrast with the devastating subsequent surge (S2) which was emplaced one hour later (Fig. 15).

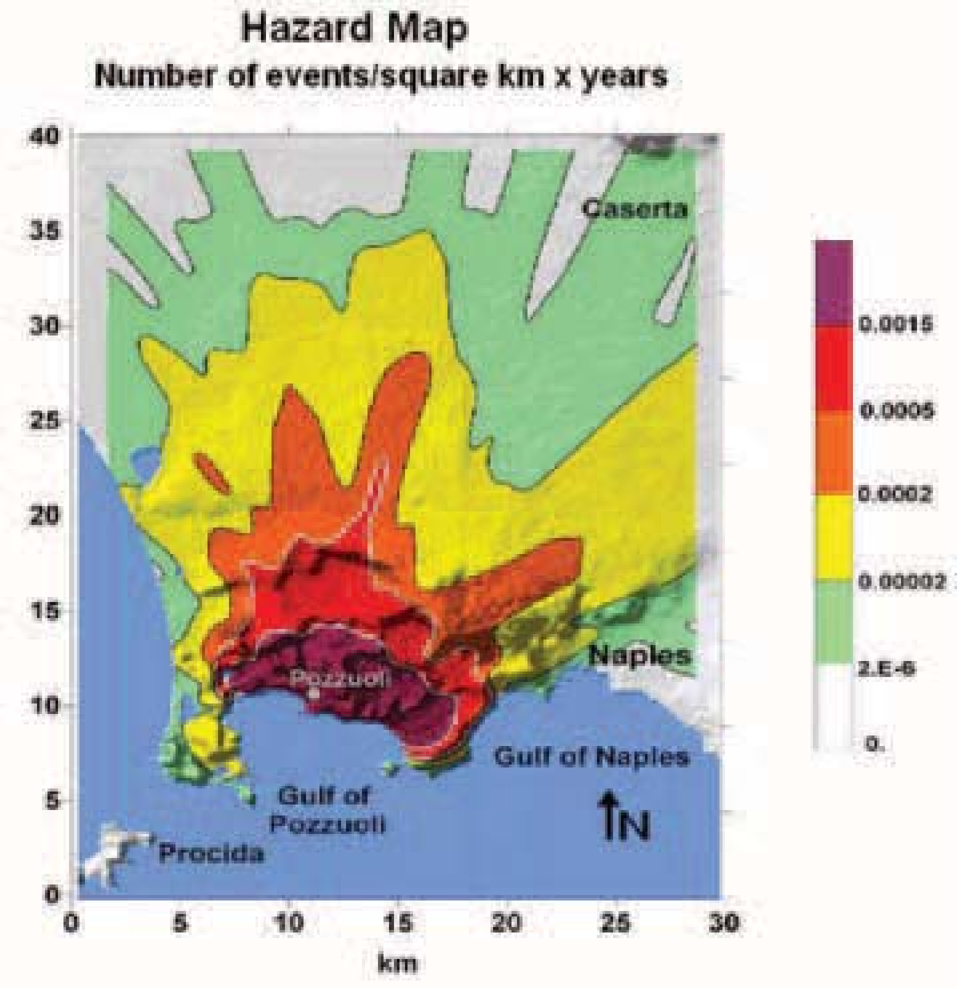
A maximum thickening of surge S1 occurred in 12 waterfront chambers (on average 3.5 m high, 3.0 m wide, and 3.5 m deep), in the suburban area, where at least 300 people, taking shelter from the eruption, died. The number of victims in the chambers, ranging between 15 and 41 individuals, and the crowding depended on the available space (Fig. 16).

Palaeomagnetic analysis of tiles found engulfed in surge S1, or lying on the sand, indicated in only a single specimen, collected at the entrance of the chamber 12, a possible emplacement temperature of near 480 °C. Analysis of 15 tiles and bricks in the overlying surge S2 deposit strongly indicates that this unit was emplaced at 425 °C. Evidence of a particularly high emplacement temperature of the pyroclastic surges is provided by the carbonization of wood. High cloud temperature, of ca. 650 °C, at a distance of 6 km from the volcano, is also suggested by numerical simulations of the pyroclastic flow.

The skeletons inside the chambers show a life-like stance, which reflects the one at the time of the surge emplacement: the individuals, all unaffected by mechanical impact, appear as if "frozen" in the instant of death, lacking evidence of voluntary self protective reaction or agony. This indicates that vital activities were inhibited in a time shorter than the conscious reaction time, thus suggesting an instantaneous death likely due to a fulminant shock syndrome (Mastrolorenzo et al., 2001).

This evidence is consistent with the occurrence of thermally-induced bone and skull fractures, feet and hand contractions, and preservation of bone connec-

Figure 17 - Pyroclastic sequence of 472 A.D. Pollena eruption in Somma Vesuviana, north of Vesuvius. The lower unit, consisting of magmatic fallout layers, is topped by the stratified Hydromagmatic sequence.



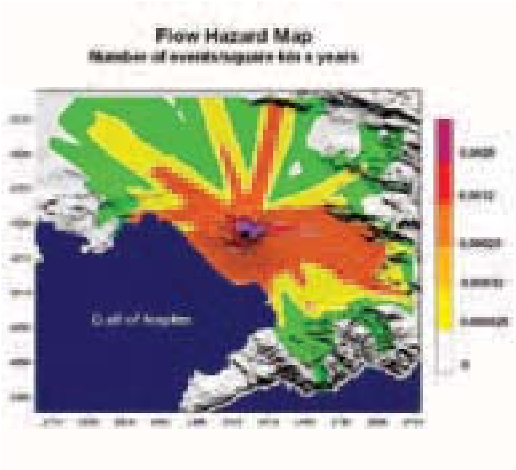


Figure 18 - Hazard map for pyroclastic currents in Campi Flegrei a) and Somma- Vesuvius b) computed as the yearly probability for each area to be affected by PDCs, and as a number of inferred PDCs. The map is based on the results of our simulation and the yearly occurrence of PDCs generating eruptions in Campi Flegrei, and at the Somma–Vesuvius in the last 12,000 years and 20,000 years respectively. Maximum occurrence of some events in 103 years is limited to within the central part of the caldera.

tions caused from the exposure to very high temperature (> 500°C), and rapid soft tissue vaporization.

3.3.3 The 472 AD Pollena sub-Plinian eruption: at the end of the Roman Empire

The 472 A.D. Pollena eruption of Somma-Vesuvius took place in the critical period of the fall of the Western Roman Empire, significantly accelerating the deterioration of the local human context in the Late Ancient age. It was an intermediate-scale explosive event including pyroclastic fall, surge, and flow (Mastrolorenzo et al., 2002). The eruption comprised a pulsating, sustained, eruption column phase, followed by pyroclastic surges and scoria flows; different from the typical Plinian eruptions of Somma-Vesuvius, hydromagmatism acted early in the event. Specific facies associations of primary and secondary volcaniclastic deposits characterize three depositional domains, including the volcano slopes, the surrounding alluvial plains, and the distal mountains of the Apennine Chain (Mastrolorenzo et al., 2002). Both volcano slopes and distal mountain slopes supplied loose pyroclastic material to the hyperconcentrated flood and debris flows that spread across the alluvial plains. The great impact of secondary volcaniclastic processes arose from: (1) the high vulnerability of the territory, due to its geomorphic context; (2) the humid climatic conditions; (3) the hydromagmatic character of the eruption; (4) the decline of land management at the end of the Roman Empire.

The deposits of the Pollena eruption belong to the highest-magnitude eruption which took place at the Somma-Vesuvius after 79 A.D. They can be traced with remarkably lateral continuity over an area extending from the Somma-Vesuvius, through the northern and eastern sectors of the Campanian Plain, as far as the western Apennine Mountains.

Four units have been recognized at the type-locality of Pollena, including, from base to top (Fig. 17):

1. unit AL: repeated clast-supported, even-parallel, surface-mantling beds, made up of well-sorted, angular, moderately vesicular, dark gray, scoria lapilli and subordinate lava lapilli, indicating an origin by fallout from an eruption column;
2. unit SL: alternating scoria fall layers and planar-to-cross-laminated ash layers, with traction sedimentation features indicative of deposition from pyroclastic surges;
3. unit S: planar to dune-bedded pyroclastic surge deposits;
4. unit F: massive, poorly-sorted, matrix-supported deposits, containing dark gray scoria and lithic lapilli and blocks.

At the top of the primary magmatic deposits, a sequence of different types of secondary syn-eruptive and post-eruptive secondary deposits have been recognized. Extrusive mud flow deposits and laminated beds, related to hyperconcentrated currents and floods, characterize the plain north and east of the volcano. Debris flows are mainly confined within Mountain slopes and in foothill fans.

Integrated geological and archaeological stratigraphies, revealed by the new excavations, document the degree of frequentation of the sites at the time of the Pollena eruption, the environmental effects of primary and secondary events, including damage to structures, and the recovery time of the terrirory after the eruption in the different domains.

Some tens of new excavations in a dozen sites relative to parts of the Roman towns of Nola and their suburbs and surrounding countrysides, include civil, religious, and commercial buildings, villas, amphitheaters, main roads, aqueducts, and other hydraulic works and agricultural work tracks.

In most of the sites, the Pollena deposits overlie already-ruined structures, thus indicating that the area was in a phase of deep decline. In some cases, thin soils and alluvial deposits pre-dating the Pollena eruption, cover ruined structures and indicate the abandonment of the site before the Pollena eruption.

Direct effects on the people are not documented in the chronicles, nor in the excavations, with the notable exception of some tens of human skeletons, which have been found within a hardened mud layer dated near the end of the V century in the Cimitile basilicae. There is evidence that these people died in a catastrophic event – possibly the church roof collapsed due to accumulation of lapilli (Pagano, 1997).

3.4 Modeling of the volcanic hazard in the Neapolitan area

In order to assess the volcanic hazard in the Neapolitan area, a numerical simulation of both concentrated and diluted primary and secondary pyroclastic density currents (PDCs) on a digital topographic model of Campi Flegrei and Somma - Vesuvius has been carried out (Fig. 18, a and b). Families of numerical flows are generated by sampling a multi-dimensional matrix of vent coordinates, flow properties, and dynamical parameters in a wide range of values, which are based on the current volcanological knowledge (Rossano et al, 1998; Rossano et al, 2003). Hazard maps are constructed from the data base of simulated flows, using a mixed deterministic-statistical approach. Results show the key role of the topography in controlling the flow dispersion. The maximum hazard related to the Campi Flegrei eruptions appears to be the NE sector of the caldera. Flows in the western sector, including the city of Naples, are shown to be efficiently hinde-

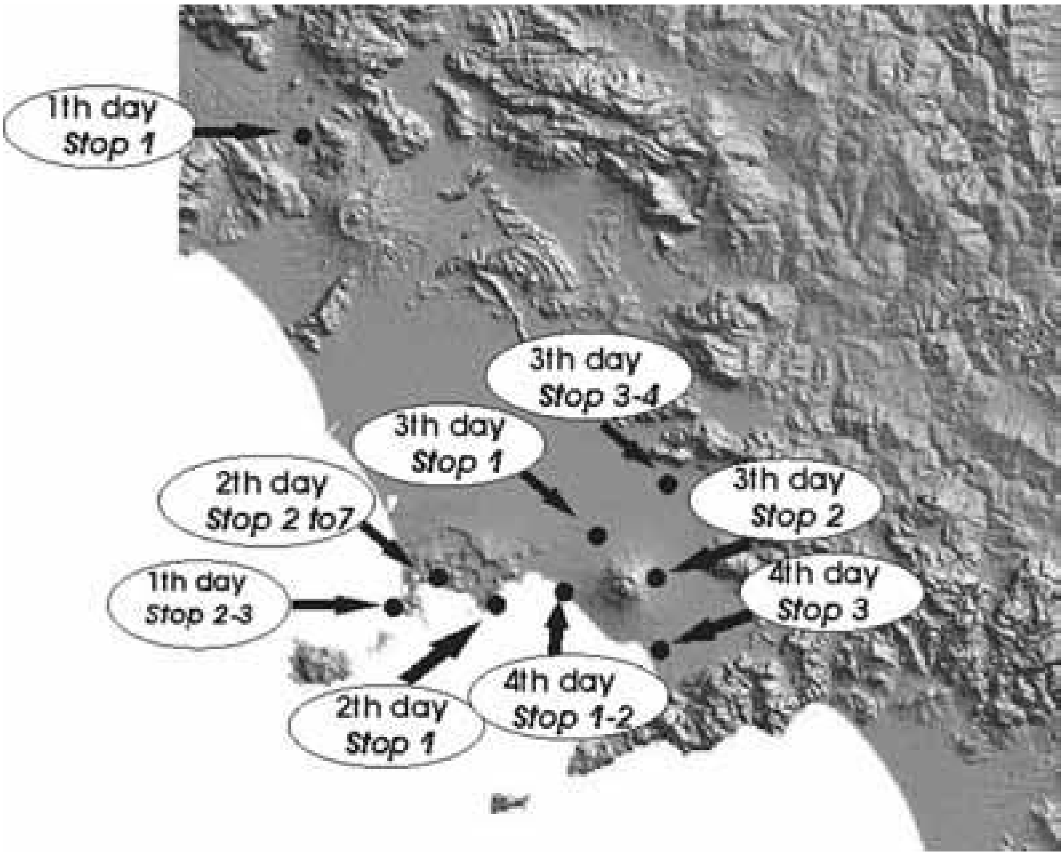


Figure 19 - Locations of the field trip stops

red by the presence of the Posillipo and Camaldoli hills at the caldera borders, thus reducing the hazard. The hazard related to the Somma-Vesuvius PDCs is mainly constrained within about 15 km from the volcano. Dynamic overpressures, related to the passage of PDCs in each point, are also provided. The results represent the first physically-based estimation of hazard from pyroclastic flows in this densely-populated area.

Field itinerary

DAY 1

Large Ignimbrite deposits of Campanian Ignimbrite and older (> 12 ka) eruptive sequences of Campi Flegrei. Distal and proximal sections of the major pyroclastic deposits will be shown in the sites of the Garigliano River, ca. 80 km north of Naples, in Calvi Risorta (Caserta,) and within the Campi Flegrei Caldera, Pozzuoli, (Naples).

Stop 1 and 2:

Calvi Risorta and the Garigliano River

Distal facies of Campanian Ignimbrite in these sites consist of a ca 10 m thick fine-grained welded tuff, with columnar jointing (10 to 20 cm prismatic columns). No vertical grading or stratification is present, and the main features of the deposit are the local changes in the sizes and geometry of columnar jointing (Fig. 20). In particular zones, the convergence of the jointing indicate non-homogeneous contraction of the hot deposits. Fine, black vesicular scoria are scattered within the ashy matrix, which mostly consists of glass shards and very rare crystals and lithics. Both the structure and grain size of the deposit represent the extreme distal evolution of the CI. In fact, the black juvenile scorias are as large as about 1 m in the proximal facies. Both in the Garigliano River, and in Calvi Risorta, the deposit infills the topographic lows with a nearly horizontal upper surface, thus indicating its origin from a dilute pyroclastic density current;

Figure 20 - Columnar jointing in the Campanian Ignimbrite formation.

however, the absence of evidence of the erosion of the underlying pre-existing ground surface, is consistent with a gentle emplacement for en-mass freezing of an expanded" pyroclastic cloud (Fig. 21).

Stop3 and 4:

Torregaveta and Acquamorta Beach, Monte di Procida (SW Campi Flegrei cadera rim)

The Torregaveta marine cliff, on the southwestern Campi Flegrei caldera rim, exhibits an extended eruptive sequence, including the pre-caldera lava domes and pyroclastic deposits, Museum Breccia and post-caldera pyroclastic sequence (Fig. 22). From the base to the top, the following units are exposed: 1) pre-caldera trachytic lava domes; 2) pre-caldera stratified pyroclastic surge and Strombolian sequence, 3) Museum Breccia, 4) post-caldera deposits, including Torregaveta tuff breccia, and 5) Neapolitan Yellow Tuff. An unconformity defines the stratigraphic relationship between the Neapolitan Yellow Tuff at the top of the sequence, and the older volcanic sequence. Breccia Museo and Neapolitan Yellow Tuff are the two most conspicuous deposits. Both are emplaced, as relatively concentrated pyroclastic density currents

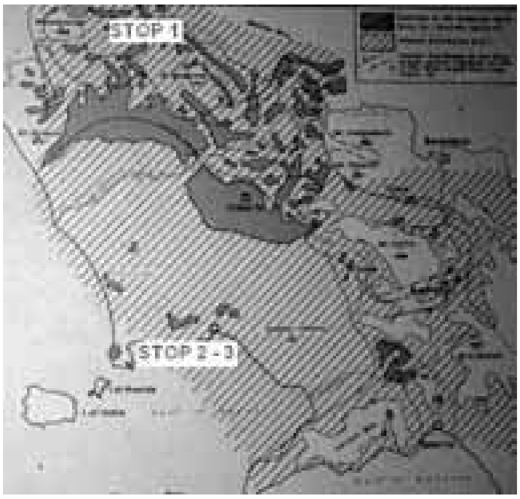


Figure 21 - Distribution of Campanian Ignimbrite deposits.

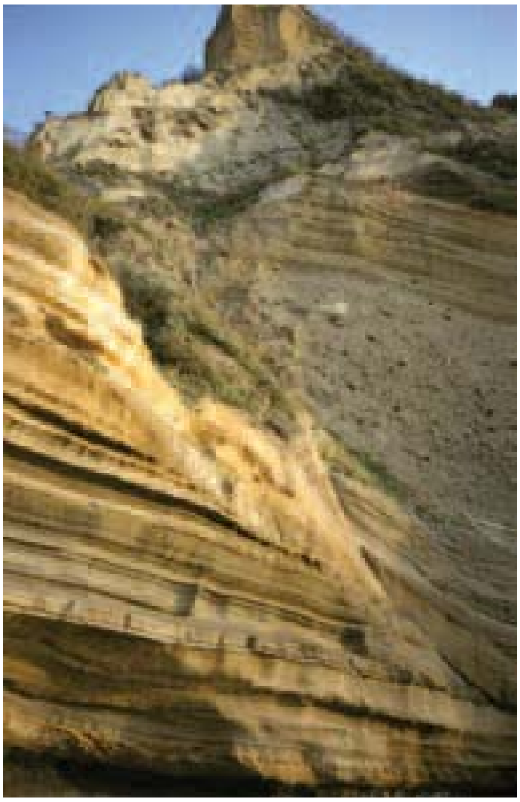


Figure 22 - Torregaveta cliff sequence of precaldera surge and Strombolian deposits, Breccia Museo, Torregaveta, Strombolian deposits and Neapolitan Yellow Tuff.

are the first events responsible for the modification of the morphological and volcano-tectonic setting of the area.

The coast of Acquamorta, a ca. 2 km long marine cliff south of Torregaveta, presents a vertical stratigraphic section of the pre-caldera and post-caldera sequence, which is described in the previous stop. The Breccia Museo is massive and ungraded at the base, and faintly stratified at top, and consists of a clast-supported pyroclastic flow deposit, containing pumice scoria and lithic lava blocks, as well as subvulcanic and sedimentary rocks. Bread crust bombs are abundant.

DAY 2

Neapolitan yellow Tuff and recent volcanic and volcano-tectonic events in Campi Flegrei caldera (from 10,000 yr B.P. to present).

La Starza terrace in Pozzuoli (8,000 to 4,500 yr B.P.) evidence of a 40 m prehistoric rapid uplift related to the peaks in volcanic activity in the center of the Campi Flegrei caldera. Stratigraphy, eruptive mechanisms, history, and mythology of the young pyroclastic volcanoes near Pozzuoli (Capo Miseno, Porto Miseno, and Nisida tuff cones, and Solfatara, Astroni, and Averno tuff rings). Onland and submerged Roman constructions around Pozzuoli Bay (Pozzuoli) are direct evidence of ground subsidence and episodic rapid uplift of the Caldera (Capo Miseno tuff cone and its submergence, Baia imperial villas, Portus Julius harbour, Serapis marketplace, Posillipo Villas). The historical pyroclastic cone of Monte Nuovo (Pozzuoli), the destruction of Tripergole village, and the related evolution of the territory.

Stop 1:

Stratigraphy and depositional structures of the Neapolitan Yellow tuff and Nisida tuff Cone: Posillipo hill and Nisida (West of Naples)

At the Posillipo section the lithified upper member of the NYT (Fig. 23) formation occurs. The tuff sequence consists of a ca 160 m thick, crudely-stratified, wavy-to-planar alternations of coarse-grained, disorganized, matrix-supported layers, thinly-laminated discontinuous beds and massive, even fine ash layers. Each thick, coarse-grained bed is delimited by a lower and an upper massive indurate fine ash bed. The deposit is emplaced on an older tuff cone of Trentaremi, consisting of a coarse-grained pumice lapilli bed, that caused the pyroclastic cloud to climb onto a steep slope, thus depositing very impressive tens of meter long inclined dune structures, recognizable on the outcrops of Posillipo hill (Fig. 24), and inside the Roman tunnel of Trentaremi which crosses the hill. The small island (about 600 m) of Nisida is constituted of a well-preserved tuff cone built up on pre-existing submerged volcanic edifices. The products are made of

Figure 23 - Surface distribution of Neapolitan Yellow Tuff along the caldera borders.

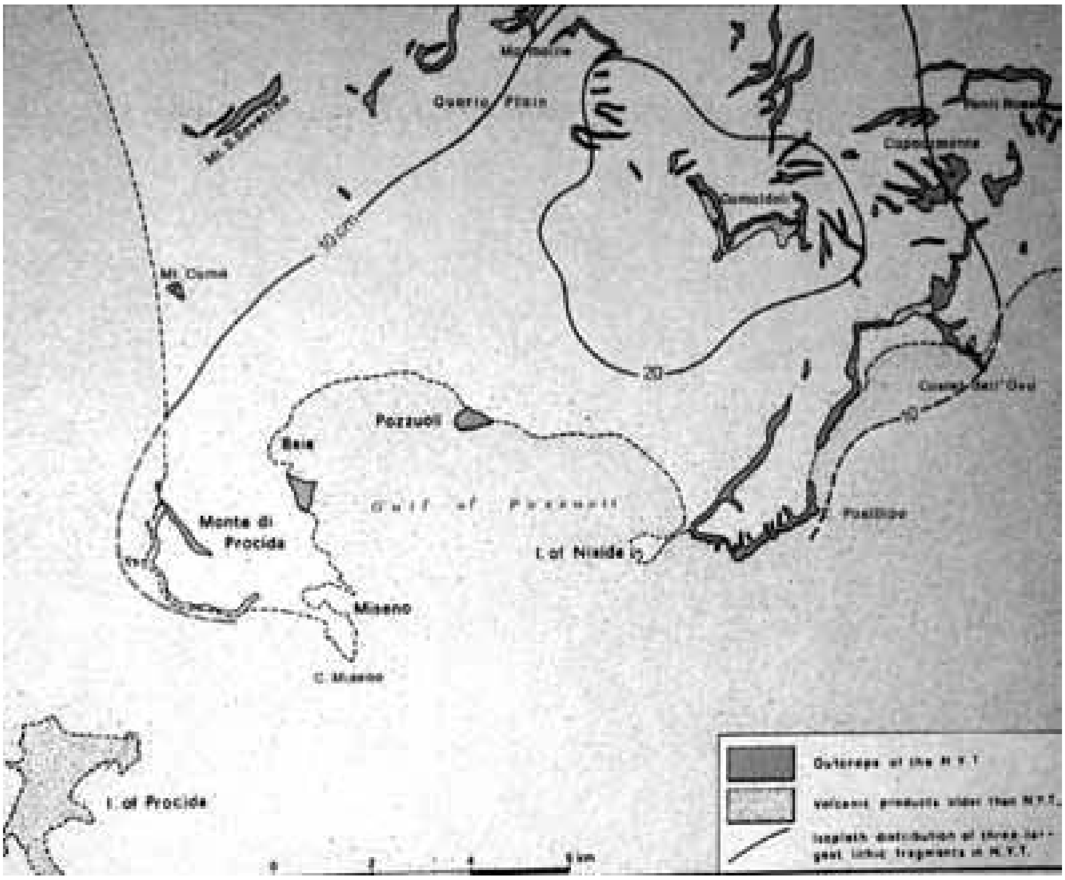


Figure 24 - The structures of Neapolitan Yellow Tuff on the walls of the Roman tunnel of the Seiano, crossing Posillipo Hill.

stratified yellow tuff, formed by highly lithified beds of ashes and pumices, containing abundant scoriae and bombs up to 50 cm in size near the crater.

Roman buildings and structures submerged at about 5 m below sea level in this part of the coast testify to the general subsidence affecting the entire caldera since ancient times. Due to its rapid decreasing from the center of the caldera, the positive bradyseism effected only subordinately the western and eastern margins of the caldera where the subsidence prevails.

Stop 2:

La Starza marine terrace

La Starza sea-cliff parallels the north coastline of Pozzuoli Bay from Monte Nuovo to Pozzuoli, and presents three marine layers separated by tephra layers erupted from Campi Flegrei (Fig. 25). The radiocarbon ages of the tephra layers indicate that these marine layers were formed during three separate transgressions of the sea, that occurred between 8,400 to 4,050 yrs ago. The carbon-14 age for a shell recovered from the uppermost marine layer has an age of 5,345+ 150 yr (Rosi and Sbrana 1987). The positions of these marine layers, tens of meters above present sea level, cannot be explained solely by eustatic sea level changes during the past 8,000 yrs. The uppermost and

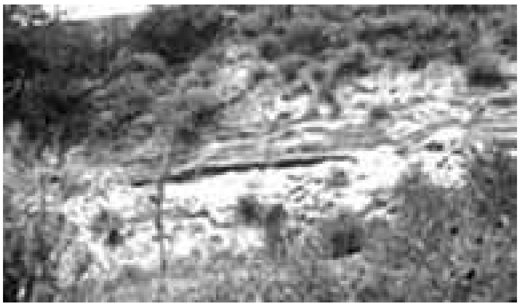


Figure 25 - Sequence of marine and pyroclastic deposits.

youngest marine layer was uplifted at least 40 m in less than 3,000 yrs. Most of this uplift occurred during a long quiescent period, from 8,000 to 4,500 yrs ago, between two major phases of volcanic activity in Campi Flegrei. However, this structure coincides with the most active central part of the caldera, also affected by bradyseism in the recent time. (Dvorak and Mastrolorenzo, 1991).

Stop 3:

Ancient and modern town of Pozzuoli and Serapeo

The first studies of slow movements at Campi Flegrei came from the observation of sea level markers on Roman coastal ruins, which were more sensitive to large, secular deformations. Serapis Temple is the most studied archaeological site. The monument has been the object of much research, beginning shortly after its excavation in 1750 (Breislak, 1792; Forbes, 1829; Niccolini, 1839, 1845; Babbage, 1847; Lyell, 1872; Gunther, 1903; Parascandola, 1947). A marine mollusc, Lithodomus lithophagus has bored into and left shells into its three standing marble columns, recording ancient relative sea level changes. Parascandola (1947), firstly delineated, using these tracks, the history of secular ground movements at Campi Flegrei. These studies have been integrated and updated by Dvorak and Mastrolorenzo (1991), who defined a reconstruction of the time evolution of ground level at the center of Pozzuoli town.

Dvorak and Mastrolorenzo (1991) reported the following description of the monument: “The excavated monument is roughly rectangular in shape (70 by 55 m), enclosed by a wall of opus lateritium (built of thin, adobe bricks and mortar) covered by marble. The lack of opus reticulatum in the foundation suggests that this monument was established before the 1st century B.C. The main entrance to Serapis opens on the seaward side and leads into a plaza outlined by a series of small rooms, which alternately open to the inside and outside of the monument. Two large rooms in the back corners of the monument have seats placed along the internal walls, suggesting that the warm spring at this site was used as part of a Roman bath. The present floor of the monument is con-structed of marble blocks that slope towards the sea, designed for drainage of rainwater through an underground channel. In 1822, while attempting to clear a channel to drain stagnant water, Niccolini (1845) discovered an older, mosaic floor 2.1 m below the present marble floor. At the center of the monument is a rotunda, which rises 1.2 m above the marble floor and was outlined by 5-m-high columns cut from granite. Near the back of the monument, in front of a semi-circular niche that forms part of the back wall, were four large columns-13 m high and 1.5 m in diameter, each constructed of a solid piece of cipolino marble. Three of these columns are still stand-ing; the fourth lies in four main pieces on the floor. The standing columns hold the most remarkable feature of this mon-ument: the surface of each column is smooth and unbroken to a height of about 4 m above the floor; the surface of the next 3 m section on each standing column is perforated all around by a mollusk, Lithodomus lithophagus, that has bored in and left shells as 5 deep as 0.1 m inside the marble (Forbes, 1829). This mollusk attaches itself just below the sea surface by boring into soft rock and building a shell casing. Many tourists to this monument during the 19th century extracted shells as a souvenir of their visit (Lyell, 1872). Today, no shells remain on these columns. Because of the depth of penetration, and the extent of these perforations, the 3-m perforated section on each standing column must have been immersed in seawater for a long time. The lower 4-m-long sections were spared damage by mollusks because these lower sections were covered by debris, and may never have been in direct contact with seawater. The upper 6-m-long sections of these columns were spared damage by mollusks because they, too, were never in direct contact with seawater, either because sea level never reached them or, if the sea did, later deposits covered and protected the upper half of each standing column. At the time of excavation in 1750, only the top few meters of each standing column rose above ground level. Based on its architecture and location, Serapis probably had three main uses during the Roman Age (De Jorio, 1820; Nicco-lini, 1845; Parascandola, 1947; Sicardi, 1979). The original Roman building may have been a temple. The parts of the mon-ument that probably date from this original use are the mosaic floor, which lies 2.1 m below the present marble floor, and was probably constructed in the mid-2nd century B.C. (Levi, 1969), and the foundation walls, constructed of opus latericium and cov-ered with marble, probably also constructed during the 2nd century. The three standing marble columns are located northeast of the central rotunda in front of the large semi-circular niche on the back of Serapis, and seats along the walls of back corner rooms suggest that this structure may also have served as a Roman thermal bath.”

The detailed reconstruction of the ground movement at Serapis is poorly constrained; however, Parascandola (1947), and Dvorak and Mastrolorenzo (1991), have described the main events on the basis of historical reports and inferences. On this basis, the Authors have found a general trend characterized by a constant rate of subsidence (11 to 14 mm/yr), interrupted by short time episodes of fast ground uplift (Fig. 26). (Tab.1,2,3)

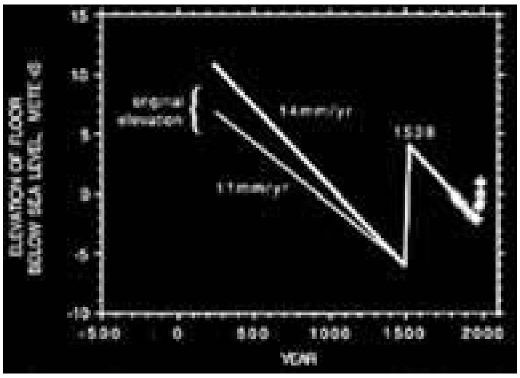


Figure 26 - History of vertical movement at Serapis. Extrapolation of a subsidence rate of 14mm/yr, suggests that the floor of the Serapis may have been about 4 m above sea level after the 1538 eruption in Campi Flegrei. If Serapis reached its maximum subsidence of 7 m below sea level during the 15th century, then uplift of about 11m occurred during the first few decades before the 1538 eruption in Campi Flegrei. Based on eyewitness accounts, uplift of a few meters occurred the two days immediately before the eruption. A constant subsidence rate of 11mm/yr can account for our estimate of 5 to 10 m for the original elevation of the tiled marble floor of Serapis. (Dvorak and Mastrolorenzo, 1991)

Stop 4:

Monte Nuovo pyroclastic cone

The deposits of the Monte Nuovo eruption cover an area of some 3.6 km^2, with a dense-rock equivalent volume of about 0.025 km^3. Four depositional units have been recognized by Di Vito et al, (1987) (Fig. 27).

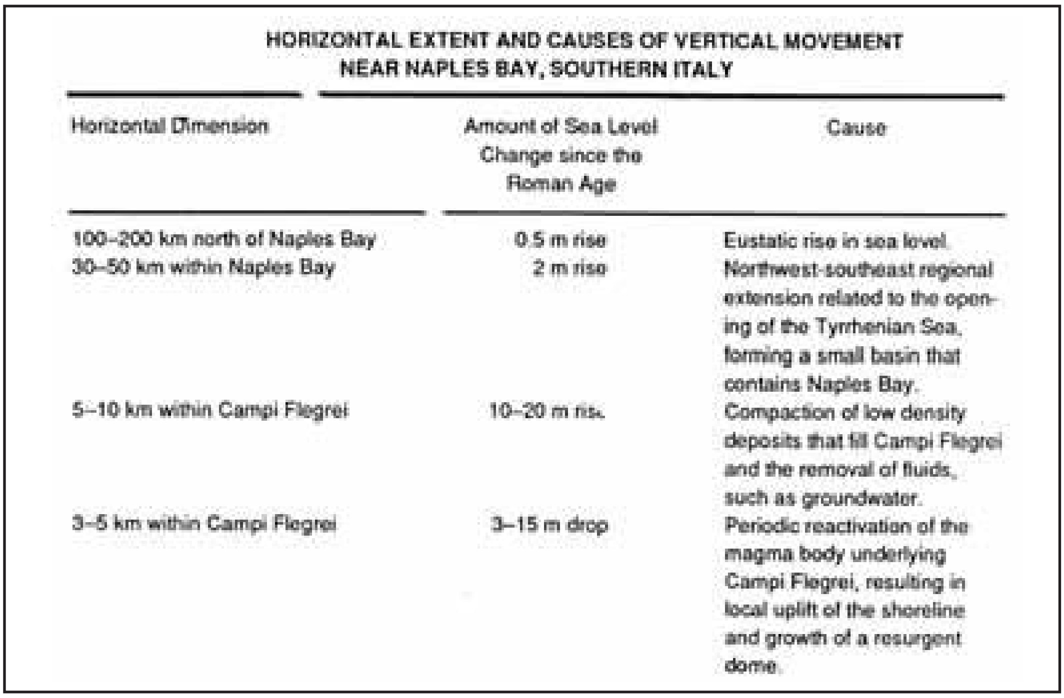
The first unit (I) is exposed in outcrops around the southern part of the volcano, with a maximum thickness of about seven meters (Fig. 28). It has a generally chaotic textural appearance, with an abundant ashy matrix containing fragments of poorly vesicular and sub-rounded pumice clasts ,and non-juvenile lava and yellow tuff fragments. Welding, pipe structures, and evidence of plastic deformation are absent in this unit, a part of which has been lithified by post-depositional mineralization (zeolitization).

The second unit (II) crops out around the whole volcano, and with an inferred maximum thickness of 60-70 meters, forms the major part of the cone. Largely unlithified, it has a textural appearance similar to unit I. The bulk of the deposit consists of an essentially chaotic arrangement of lithic fragments of lava and yellow tuff, up to about 10 cm across and rounded pumice set in a matrix of coarse ash. Close to the vent, however, a weak undulatory banding is apparent, owing to the arrangement of zones rich in large pumice fragments 30 cm or less in diameter. Sparse fragments of jars, scattered within the I and II units, likely derive from the Tripergole village, buried by the eruption.

COMPARISON OF ASSUMPTIONS USED TO DERIVE A 2,000-YEAR HISTORY OF VERTICAL MOVEMENT AT SERAPIS

Parascandola (1947)	This Paper
The marble-tiled floor was 2 m above sea level during the last major restoration of this structure in the 3rd century A.D.	The marble-tiled floor was 5 to 10 m above sea level during the last major restoration of this structure in the 3rd century A.D.
The highest level of perforations on the three standing marble columns represents the highest stand of sea level.	The highest level of perforations on the three standing marble columns represents the highest stand of sea level.
Twelve mm/yr has been the average subsidence rate since the 1820s.	Fourteen mm/yr has been the average subsidence rate since the 1820s.
Long term subsidence and uplift rates are equal in Pozzuoli Bay; maximum subsidence occurred during the 10th century.	No historical evidence for several meters of gradual uplift occurring earlier than a century before the 1538 eruption in Pozzuoli Bay; a document dated 1441 indicates that the littoral plain seaward of the Starza sea cliff was still covered by the sea; a statement by Loffredo indicates that part of this littoral plain was above sea level in about 1530.
The littoral plain seaward of the Starza sea cliff was still below sea level in 1530.	Part of the littoral plain seaward of the Starza terrace was above sea level during the early 1500s, implying that a few meters of uplift had occurred since the mid-1400s; the rise above sea level of this littoral plain is the land mentioned in the two royal edicts dated 1503 and 1511.
Uplift of 7 m occurred at Serapis during the two days immediately before the 1538 eruption.	Uplift of as much as 5 m occurred during the two days immediately before the 1538 eruption; the greatest amount of uplift occurred at the eruptive site; a lesser amount occurred at Serapis.
Rapid subsidence of about 5 m occurred during several decades after the 1538 eruption.	No evidence for rapid subsidence after the 1538 eruption.

Table 1 - (from Dvorak and Mastrolorenzo, 1991)



HORIZONTAL EXTENT AND CAUSES OF VERTICAL MOVEMENT NEAR NAPLES BAY, SOUTHERN ITALY

Horizontal Dimension	Amount of Sea Level Change since the Roman Age	Cause
100–200 km north of Naples Bay	0.5 m rise	Eustatic rise in sea level.
30–50 km within Naples Bay	2 m rise	Northwest-southeast regional extension related to the opening of the Tyrrhenian Sea, forming a small basin that contains Naples Bay.
5–10 km within Campi Flegrei	10–20 m rise	Compaction of low density deposits that fill Campi Flegrei and the removal of fluids, such as groundwater.
3–5 km within Campi Flegrei	3–15 m drop	Periodic reactivation of the magma body underlying Campi Flegrei, resulting in local uplift of the shoreline and growth of a resurgent dome.

Table 2 - Horizontal extent and causes of vertical movement near Naples bay, southern Italy (from Dvorak and Mastrolorenzo, 1991)

The third unit (III), covers most of the outer flanks of the main cone. With a relatively even radial distribution around the vent, the deposit thins from about 3-2 meters near the top of the cone, to less than one meters towards its base. Three layers may be distinguished, massive gray ash bed sandwiched between layers of black scoria, containing angular fragments of denser juvenile material, and occasional pieces of pale, moderately vesicular pumice.

The fourth unit (IV), is confined within a small depression on the southern outer slope of the volcano, below the crater rim (Fig. 28). In a transverse cross section, it pinches out laterally over a few tens of metersl and varies in thickness from a maximum of 25 meters at its margins. It consists of two layers of black scoria separated by a thin, irregular layers of ash. The scoria are coarse and angular, and show no evidence of welding or plastic deformation.

Stop 5:

Averno maar

Averno maar consists of two main lithological units (Mastrolorenzo, 1994): a lower coarse-grained fallout unit and an upper unit stratified pyroclastic surge unit

Figure 27 - Distribution of the products of the Mt. Nuovo eruption.

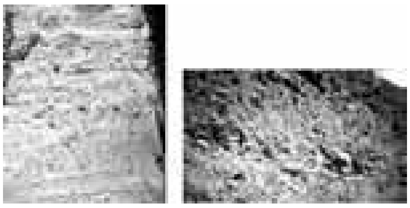


Figure 28 - First hydromagmatic unit of Monte Nuovo (left) and final IV unit scoria deposit (right).

(Fig. 29 and 30). The lower unit comprises an alternation of grain-supported fallout lapilli tuff with abundant lithic blocks (mainly in the proximal outcrops and in the basal part), and subordinate fine-grained, wavy-to-massive wet surge bedsets. The fallout layers consist of juvenile angular trachytic pumice lapilli, more dense scoriaceous lapilli, and bombs as well as rounded, yellow tuff blocks and trachyte lithics blocks derived from the underlying volcanic deposits. The upper units consist of wavy-to-planar fine ash bedsets, containing continuous laminae of matrix-supported, fine, rounded pumice lapilli.

Crater wall section: On the crater wall, the lower unit is a 10 m thick sequence, consisting of ungraded to normal graded, coarse lapilli and block fallout layers, interbedded with discontinuous matrix supported beds, containing rare pumice lapilli and large ballistic lithic blocks. The largest blocks exceed 0.5 m in diameter at the base of the lower unit, and form a large impact structured on the paleosol. The upper unit is exposed on the northern inner crater wall, with a thickness ranging between about 25 and 50 m, depending on the morphology of the older tuff relicts. The unit is poorly-sorted and nearly structureless at the base, becoming finer and better stratified upsection. At the top, the unit consists of alternating centimeter scale ash beds and rounded lapilli layers.

North-eastern outer crater section: The lower unit shows a better defined stratification, comprising at least five thinner, finer and better sorted fallout layers, and relatively thicker intercalated fine beds,

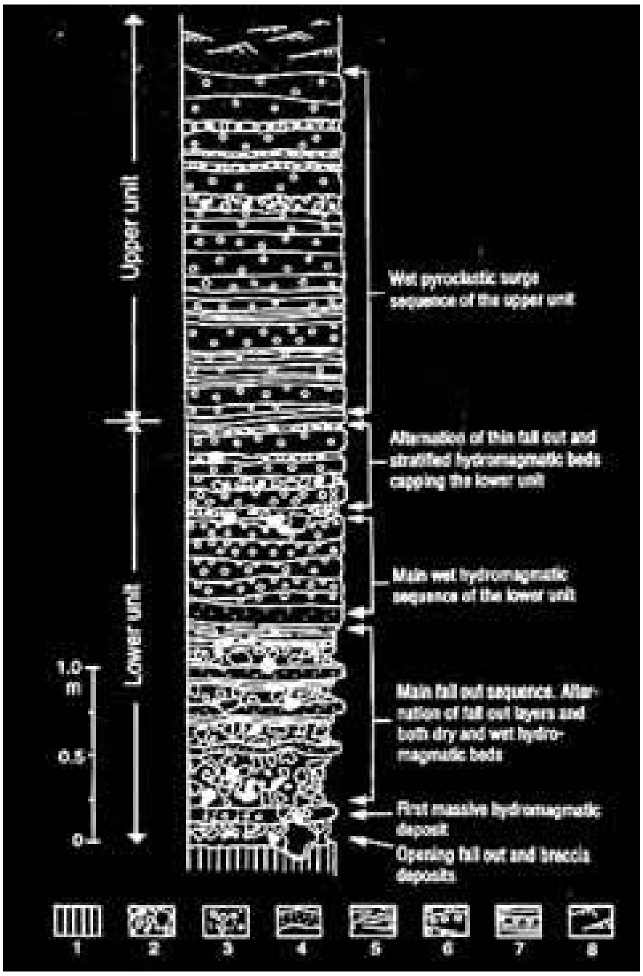
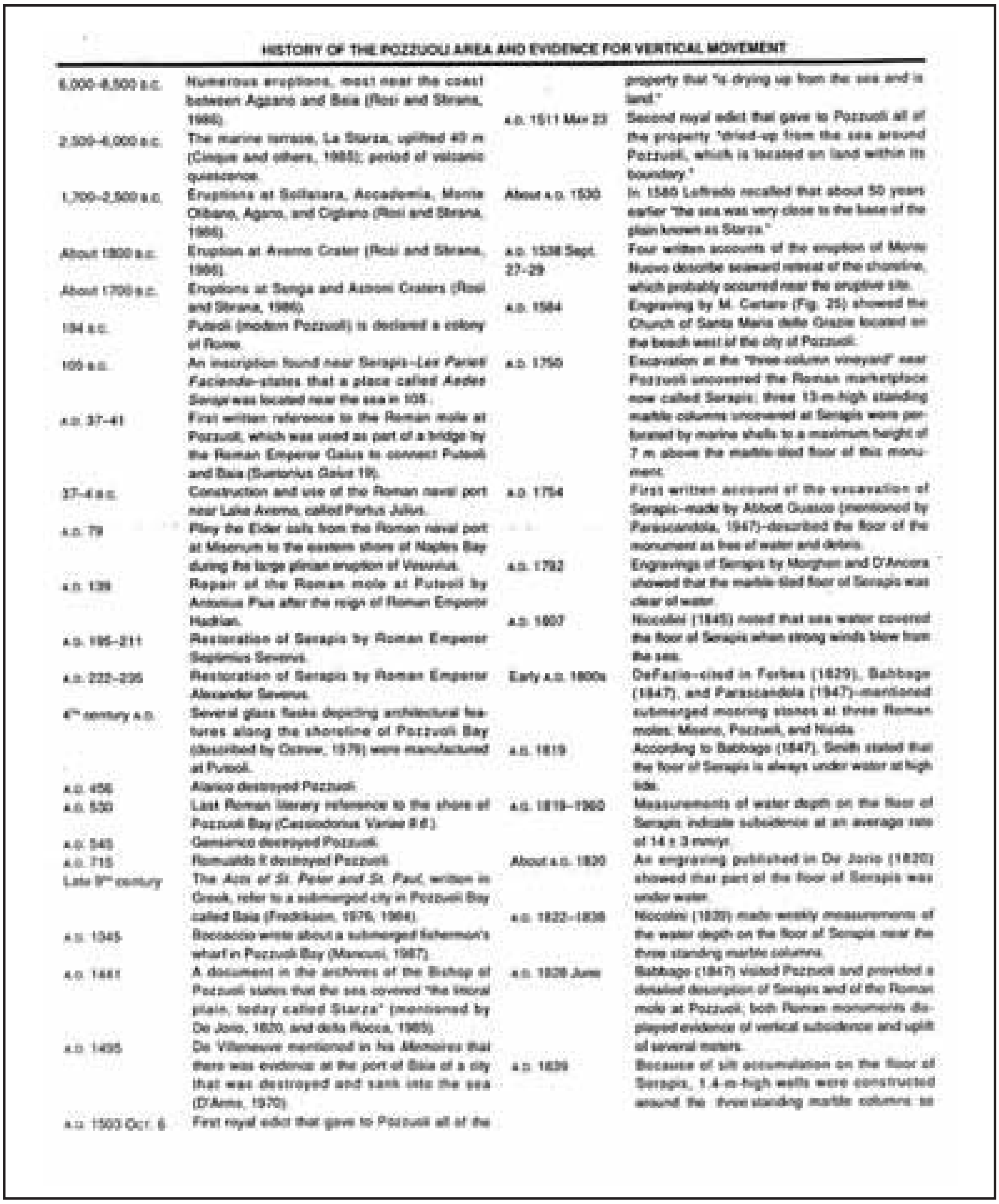


Figure 29 - Schematic stratigraphic section through a most complete exposure of the two main units and associated facies on the north eastern outer tuff ring slope. Lithological symbols: 1, Palaeosoil dated at 3,700 years BP; 2, open framework, grain-supported, well-sorted pumice lapilli layers, with tuff blocks and scoriaceous bombs (fallout deposits); 3, massive, poorly-sorted, matrix-supported beds forming the first hydromagmatic episodes; 4, continuous, massive, moderately-to-highly cohesive, very fine ash and accretionary lapilli beds intercalated with the fallout layers; 5, discontinous laminated ash and fine rounded lapilli bedsets; 6, fine grained cross-bedded to waved bedsets with accretive lapilli (the main wet pyroclastic surge deposits of the lower unit); 7, waved-to-planar, thick bedset of finely-stratified ash layers with accretive lapilli of the upper unit; and 8, post-eruptive reworked layers (Mastrolorenzo, 1994)



HISTORY OF THE POZZUOLI AREA AND EVIDENCE FOR VERTICAL MOVEMENT

6,000–8,500 B.C.	Numerous eruptions, most near the coast between Agnano and Baia (Rosi and Sbrana, 1986).
2,500–4,000 B.C.	The marine terrace, La Starza, uplifted 40 m (Cinque and others, 1985); period of volcanic quiescence.
1,700–2,500 B.C.	Eruptions at Solfatara, Accademia, Monte Olibano, Agano, and Cigliano (Rosi and Sbrana, 1986).
About 1800 B.C.	Eruption at Averno Crater (Rosi and Sbrana, 1986).
About 1700 B.C.	Eruptions at Senga and Astroni Craters (Rosi and Sbrana, 1986).
194 B.C.	Puteoli (modern Pozzuoli) is declared a colony of Rome.
105 B.C.	An inscription found near Serapis–*Lex Parieti Faciendo*–states that a place called *Aedes Serapi* was located near the sea in 105.
A.D. 37–41	First written reference to the Roman mole at Pozzuoli, which was used as part of a bridge by the Roman Emperor Gaius to connect Puteoli and Baia (Suetonius *Gaius* 19).
37–4 B.C.	Construction and use of the Roman naval port near Lake Averno, called Portus Julius.
A.D. 79	Pliny the Elder sails from the Roman naval port at Misenum to the eastern shore of Naples Bay during the large plinian eruption of Vesuvius.
A.D. 139	Repair of the Roman mole at Puteoli by Antonius Pius after the reign of Roman Emperor Hadrian.
A.D. 195–211	Restoration of Serapis by Roman Emperor Septimius Severus.
A.D. 222–235	Restoration of Serapis by Roman Emperor Alexander Severus.
4th century A.D.	Several glass flasks depicting architectural features along the shoreline of Pozzuoli Bay (described by Ostrow, 1979) were manufactured at Puteoli.
A.D. 456	Alarico destroyed Pozzuoli.
A.D. 530	Last Roman literary reference to the shore of Pozzuoli Bay (Cassiodorus *Variae 8.8*).
A.D. 545	Gensarico destroyed Pozzuoli.
A.D. 715	Romualdo II destroyed Pozzuoli.
Late 9th century	The *Acts of St. Peter and St. Paul*, written in Greek, refer to a submerged city in Pozzuoli Bay called Baia (Fredrikson, 1976, 1984).
A.D. 1345	Boccaccio wrote about a submerged fishermen's wharf in Pozzuoli Bay (Mancusi, 1987).
A.D. 1441	A document in the archives of the Bishop of Pozzuoli states that the sea covered "the littoral plain, today called Starza" (mentioned by De Jorio, 1820, and della Rocca, 1985).
A.D. 1495	De Villeneuve mentioned in his *Memoires* that there was evidence at the port of Baia of a city that was destroyed and sank into the sea (D'Arms, 1970).
A.D. 1503 Oct. 6	First royal edict that gave to Pozzuoli all of the property that "is drying up from the sea and is land."
A.D. 1511 May 23	Second royal edict that gave to Pozzuoli all of the property "dried-up from the sea around Pozzuoli, which is located on land within its boundary."
About A.D. 1530	In 1580 Loffredo recalled that about 50 years earlier "the sea was very close to the base of the plain known as Starza."
A.D. 1538 Sept. 27–29	Four written accounts of the eruption of Monte Nuovo describe seaward retreat of the shoreline, which probably occurred near the eruptive site.
A.D. 1584	Engraving by M. Cartaro (Fig. 25) showed the Church of Santa Maria delle Grazie located on the beach west of the city of Pozzuoli.
A.D. 1750	Excavation at the "three-column vineyard" near Pozzuoli uncovered the Roman marketplace now called Serapis; three 13-m-high standing marble columns uncovered at Serapis were perforated by marine shells to a maximum height of 7 m above the marble-tiled floor of this monument.
A.D. 1754	First written account of the excavation of Serapis–made by Abbott Guasco (mentioned by Parascandola, 1947)–described the floor of the monument as free of water and debris.
A.D. 1792	Engravings of Serapis by Morghen and D'Ancora showed that the marble-tiled floor of Serapis was clear of water.
A.D. 1807	Niccolini (1845) noted that sea water covered the floor of Serapis when strong winds blew from the sea.
Early A.D. 1800s	DeFazio–cited in Forbes (1829), Babbage (1847), and Parascandola (1947)–mentioned submerged mooring stones at three Roman moles: Miseno, Pozzuoli, and Nisida.
A.D. 1819	According to Babbage (1847), Smith stated that the floor of Serapis is always under water at high tide.
A.D. 1819–1960	Measurements of water depth on the floor of Serapis indicate subsidence at an average rate of 14 ± 3 mm/yr.
About A.D. 1820	An engraving published in De Jorio (1820) showed that part of the floor of Serapis was under water.
A.D. 1822–1838	Niccolini (1839) made weekly measurements of the water depth on the floor of Serapis near the three standing marble columns.
A.D. 1828 June	Babbage (1847) visited Pozzuoli and provided a detailed description of Serapis and of the Roman mole at Pozzuoli; both Roman monuments displayed evidence of vertical subsidence and uplift of several meters.
A.D. 1839	Because of silt accumulation on the floor of Serapis, 1.4-m-high walls were constructed around the three standing marble columns so

Table 3 - History of the Pozzuoli area and evidence for vertical movements (from Dvorak and Mastrolorenzo, 1991)

which exhibit dune-type cross-stratification, and contain accretionary lapilli. Continuous, 2-50 cm thick pisolitic ash beds drape some of the pyroclastic surge bedsets. Thin indurate beds of vesiculated tuff, characterized by the presence of irregular millimeter-sized cavities, occur at different levels. In the outer rim section, the upper unit thins and shows lateral facies changes: the fine ash bedsets change from low angle wavy and cross-bedded-to-planar facies (Fig. 31).

Figure 30 - Isopach maps of the lower fallout unit and the upper surge unit. The Control of the topography on the emplacement of the pyroclastic surge is evidenced by the change of ashy sequence thickness, mostly near the southern and western hilly areas. The deposit thickness is expressed in meters (Mastrolorenzo,1994)

Stop 6:

The submerged town of Baia

A detailed description of the submerged Town of Baia is reported by Dvorak and Mastrolorenzo (1991), that suggests a net subsidence of about 8 m since Roman times. Extensive use of opus reticulatum in wall construction at this site indicates that most of the city was constructed between the 1st century BC and the 2nd century AD. The last pier of the Roman breakwater lies about 800 m from shore. An attempt was made in 1959 to map the underwater ruins at Baia systematically. Based on maps published in Lamboglia (1959), the landward end of the Roman breakwater is at a depth of about 10 m. Roadways built of individual paving stones, some with ruts made by wagon wheels, and doorways leading into buildings and courtyards, are common at depths shallower than 7 m. The deepest feature was a straight channel, probably for drainage, several meters long, about 0.1 m wide, and 0.15 m deep, at a depth of 8 m, and located near the landward end of the Roman breakwater. The deepest Roman stonework on the surviving piers of the breakwater is at a depth of 18 m.

Stop 7:

Miseno tuff cone. The Roman thermal area and villas.

Capo Miseno tuff is the relict of a stratified and very highly lithified tuff cone (Figs. 32 and 33). The tuff, yellow in color, is formed by inclined layers of pumice/lapilli in an altered ashy matrix, with a massive planar and cross-laminated structure.

Part of the crater is preserved only to the west, whi-

Figure 31 - Alternation of the stratified fine ash surge beds and fallout layers of Averno, north of the crater.

le the northern slope is a small sector of the outer volcano slope. The lighthouse is located near the convergence between the inner and outer crater slopes (visible from the sea). East of capo Miseno, there is Porto Miseno volcano, which is a relict of a low rim tuff ring featuring astratified yellow tuff. The wide crater was the Harbour of Pliny the Elder's Roman navy fleet.

Figure 32 - The Capo Miseno lighthouse at the top Tuff Cone cliff, at the intersection between inner and outer crater slope stratifications.

DAY 3

Avellino Plinian and Pollena subplinian formations of Somma-Vesuvius

Stop 1:

Proximal facies of Avellino Plinian formation

In the Novelle quarry (W -NW of Somma -Vesuvius) crops out the most proximal section of the Avellino Plinian eruption (3550 yrs BP), including all the deposits related to the initial magmatic and following phreatomagmatic phases of this eruption (Fig. 34). At the base of the sequence crop out the deposits of the opening phase of the eruption, consisting of coarse breccia and pumice- lapilli fallout units (Fig. 35). This basal sequence is topped by a thick stratified and massive surge sequence. From the base to the top, a lower and upper member have been identified. The lower member includes the deposits of the mostly magmatic episodes related to the substained column of the first Plinian phase. From the base to the top, the following units have been identified:1) a basal homogeneous massive thin ash-layer; 2) a 0.6 m thick inversely graded dark gray lithic and pumice lapilli bed (unit 1 fb) grading upwards to a white pu-

Figure 33 - Submergence of the Roman grottos on the beach on the north western coast of Capo Miseno.

mice lapilli layer (1f); 3) a ca. 1.8 m thick sequence of a massive layer, consisting of coarse lapilli and block in a fine ash matrix, interbedded with fine ash units; 4) a 0.6 m thick white pumice lapilli fallout bed with dispersed blocks (2f white pumice unit); 5) a 2 m thick massive moderate-to-poorly sorted gray pumice lapilli and block fallout layers, with interbedded ash and sand layers (3f gray pumice unit).

The upper member includes the deposits of the second phase of the eruption, deriving from a Plinian column collapse, which follows the climatic phase of the eruption (Fig. 36). From the base to the top, the following units have been identified : 1) a massive coarse-grained lapilli and block pyroclastic flow deposits; 2) ca. 10 m thick stratified and massive pyroclastic surge ash and lapilli beds (units from 3s to 8s); 3) the fine-grained thickly bedded deposits, consisting of undulatory waved bedsets with cross-laminations. Climbing dunes are present mostly in the middle of the sequence where intense erosional episodes took place. Massive poorly-sorted lenses, related to leeside and stooside (?) accumulation of lapilli and blocks, resulted from the erosional effects of the more violent surges on the fallout beds.

Stop 2:

The crater of Vesuvius

The present Vesuvius crater results from the effusive and explosive eruptions occurring in the last few centuries. In particular, in the upper part of the crater, the contact between the 1906 and 1944 crater structures is exposed. From the crater rim of Vesuvius, a view of the summit area of the Somma-Vesuvius volcano, the Somma caldera, the most recent 1944 lava flows and small scale hot debris avalanches is allowed.

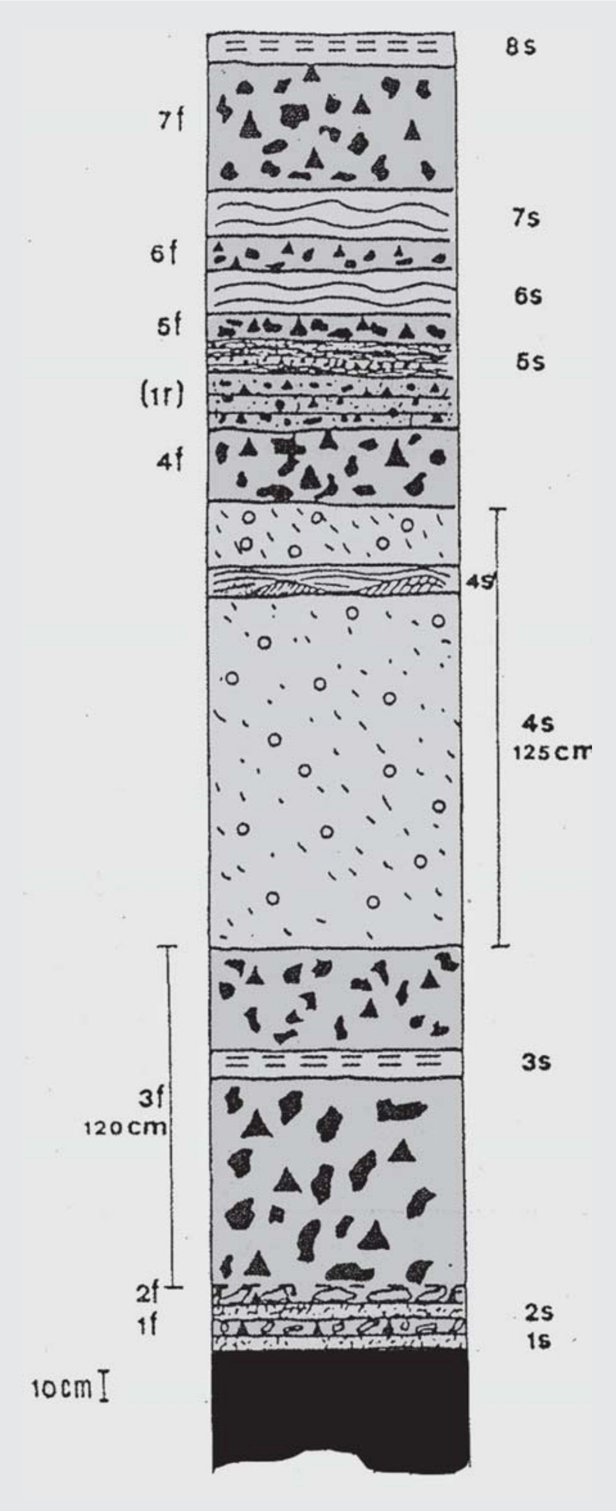


Figure 34 - Stratigraphic section of the Avelliono Plinian eruption at Lagno di Trocchia near S.Anastasia. (Rolandi et al., 1993)

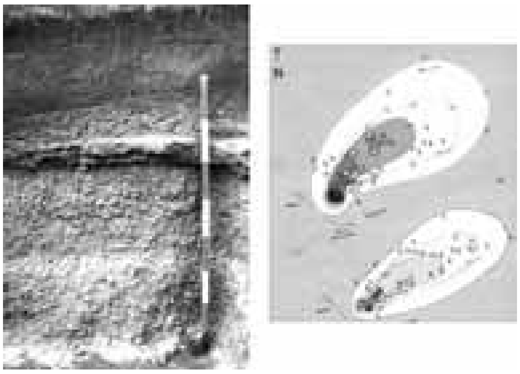


Figure 35 - Isopach maps of the fallout of the Avellino formation. The two major air-fall layers which overlie the basal thin layer 1f are represented; the white member of the plinian pumice deposit 2f; and the gray pumice member 3f. (Rolandi et al., 1993)

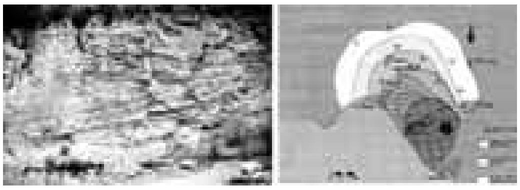


Figure 36 - Isopach map and facies distribution of the Avellino base surge deposits. (Rolandi et al., 1993)

Stop 3:

The Pollena (472 AD) eruption and the Roman amphiteatre at Nola

The town of Nola, 15 km from Vesuvius, is located in the alluvial plain north of Vesuvius, surrounded to the east and north by the Mesozoic carbonate mountains of the Campanian Apennine. Since the prehistoric age, due to its position, the Nola area has been affected by primary and secondary deposits of various eruptions of Vesuvius.

In particular the pyroclastic fallout and surge deposits interbedded with secondary debris flow lahars and flood deposits related to the eruption of Ottaviano (7900 yrs BP), Avellino (3550 yrs BP), and Pollena (472 AD), are recognizable in the first few meters of the shallow stratigraphic sequence exposed in the excavations.

Nola Roman Amphitheatre (Fig. 37), excavated between 1996 and 2001, was buried by the primary and secondary deposits of the 472 AD eruption (Fig. 38). From the base to the top, two units have been recognized: 1) scoria fallout, from a sub-stained eruption column interbedded with ash layers, 2) brownish-gray, massive ungraded, cohesive debris flow deposits; 3) brownish-gray, matrix-supported, massive, high matrix-strength debris flow. The whole section, with an average thickness of ca 4 m, is topped by younger paleosoils.

Figure 37 - First century BC Roman amphitheater of Nola. (from Mastrolorenzo et al., 2002)

Stop 4:

The archaeological Museum of Nola.

The archaeological Museum of Nola preserves collections of findings dated from prehistoric to mediaeval age found within the stratigraphic sequence of the Nola districts. Most of the findings are relative to the time interval between the Avellino and 472 AD eruptions, collected from the sites affected by these two events. The reconstruction of the sites, and the detailed archeological and volcanological stratigraphy, are also documented.

DAY 4

The 79 A.D. Plinian eruption of Vesuvius: the volcanic stratigraphy and effects on people and structures in Herculaneum, Oplonti, and Pompeii an Stabia (SE of Naples).

Stop 1:

The Roman town of Herculaneum

The archeological excavations of the Roman town of Herculaneum which was buried by the 79 AD pyroclastic flow and surge, is revealed under the stratigraphy of pyroclastic units, and shows the effects of the emplacement on the structures of objects and people (Fig. 39 and 41). A ca. 20 m thick pyroclastic tuff deposit, exposed on the southern side of the excavation, exhibits the products of the entire eruptive episode following the climatic phase of the Plinian sustained column. Relatively thin, mostly fine-grained horizontal pyroclastic surges are alternated with thick, massive, coarse matrix-supported pyroclastic flow units. The base of the sequence coincides with the level of the ancient coast line. From the base to the top, S1 to S6 surges alternating with F1 to F6 pyroclastic flows, are exposed (Fig. 40). At the base of the sequence, directly overlying the older tuff substratum of the Roman beach, crops out the 20 to 90 cm thick ashy, massive cohesive first surge (S1). This layer fills twelve water front chambers, where ca two hundred skeletons were found. This ashy layer is topped by a ca 1 m thick, coarse, fine-depleted second surge (S2) deposit. In some places, between the two layers, the massive first pyroclastic flow deposit is interbedded. The second surge (S2), is overtopped by ca 3 m thick matrix-supported, strongly cohesive pyroclastic flow (F2). In contrast with the first surge, which does not includes coarse fragments, the second pyroclastic surge is rich in blocks, tiles, bricks, columns, and wall fragments, deriving from the buildings demolition thus suggesting a high dynamic overpressure of the pyroclastic cloud. Groups of tens of skeletons are still present in some of the chambers, on the floor a few cm above the chamber floor imbedded within the ashy first surge.

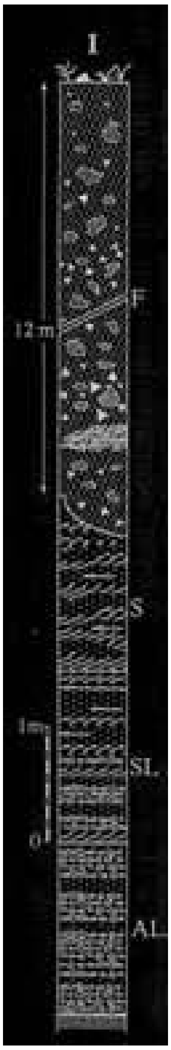


Figure 38 - Stratigraphic section of the primary deposits of the 472 AD Pollena eruption. The sequence is topped by the secondary deposits (debris flows, high particle concentrated current) from Mastrolorenzo et al., 2002

Figure 39 a and b - Stratigraphy of the A.D. 79 volcanic deposits on Herculaneum beach.

Stop 2:

The Roman Villa of Oplonti

The Roman villa of Oplontis, discovered in 1967 near the Torre Annunziata, south of Vesuvius, is one of the most complete sites for the study of the entire depositional sequence of the 79 A.D. plinia eruption (Figs 42 and 43). The ca. 5 m thick stratigraphic section, exposed within the excavations, comprise all the lapilli fall out units, the interbedded pyroclastic surge, and the upper pyroclastic surge and flow units. The evidence of roof and wall collapse, due to the accumulation of fallout lapilli, as well as the effects of the impact of pyroclastic flows and surge on buildings and trees, are well preserved in the site.

Stop 3:

Pompeii

The excavation of the Roman town of Pompeii has revealed the most conspicuous evidence of the effects of the devastating 79 A.D. Plinian eruption (Fig. 44). Roofs and wall collapses associated with the first phase of lapilli fall, and to the passage of dilute (surge) and concentrate (flow) pyroclastic density current are evident. The recently excavated house of Casti Amanti, facing the Via dell'Abbondanza (the main road of Pompeii), presents a complete assortment of the effects caused by the fall out and pyroclastic surge and flows on the structure and animals. The pyroclastic sequence exposed outside and inside the house, consist of the alternation of pumice lapilli beds, and planar and stratified undulatory fine-grained surge beds. Evidence of wall failures and collapses, likely caused by earthquakes occurred before and during the eruption, have been also recognized.

Figure 40 - The Roman town of Herculaneum, with Vesuvius in the background.

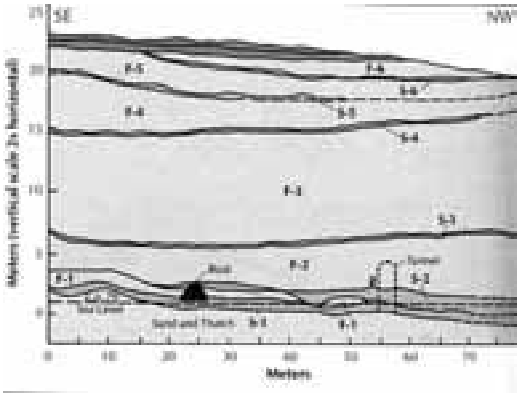


Figure 41 - Stratigraphy of the pyroclastic flow and surge at Herculaneum.

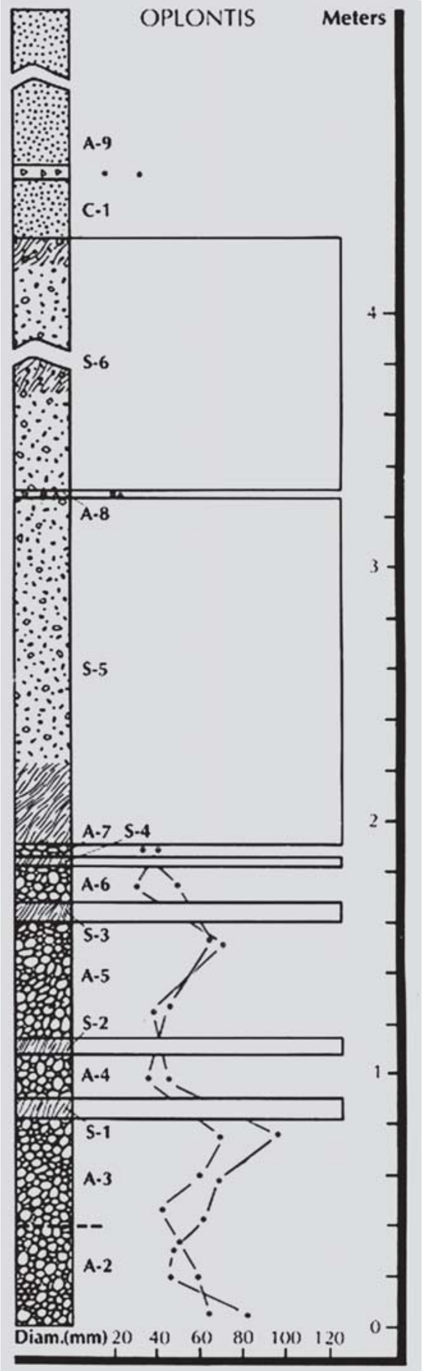


Figure 42 - Stratigraphic section of the A.D. 79 deposit at Oplonti. Note the pyroclastic flow layers on top of S-5 and S-6. Thin, cohesive, ashy surge at top of the fallout deposit. (Sigurdsson et al., 1985)

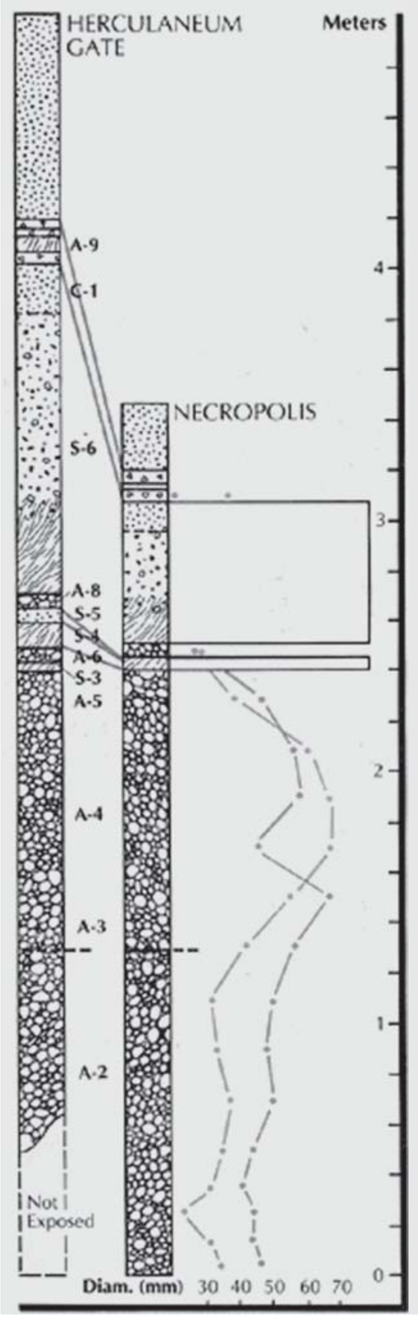


Figure 44 - Stratigraphic sections of the A.D.79 deposit near Pompeii, showing the variation in the deposit between a section at the Herculaneum Gate, northwest of the city, and at the Necropolis, southeast of the city. Also shown is the variation of maximum diameter of pumice (red), and lithics (blue) in the fall deposits. (Sigurdsson et al., 1985)

Figure 43 - 79 A.D. pyroclastic sequence in the Archeological site of Oplonti. Pyroclastic surges, basal, and fallout sequence.

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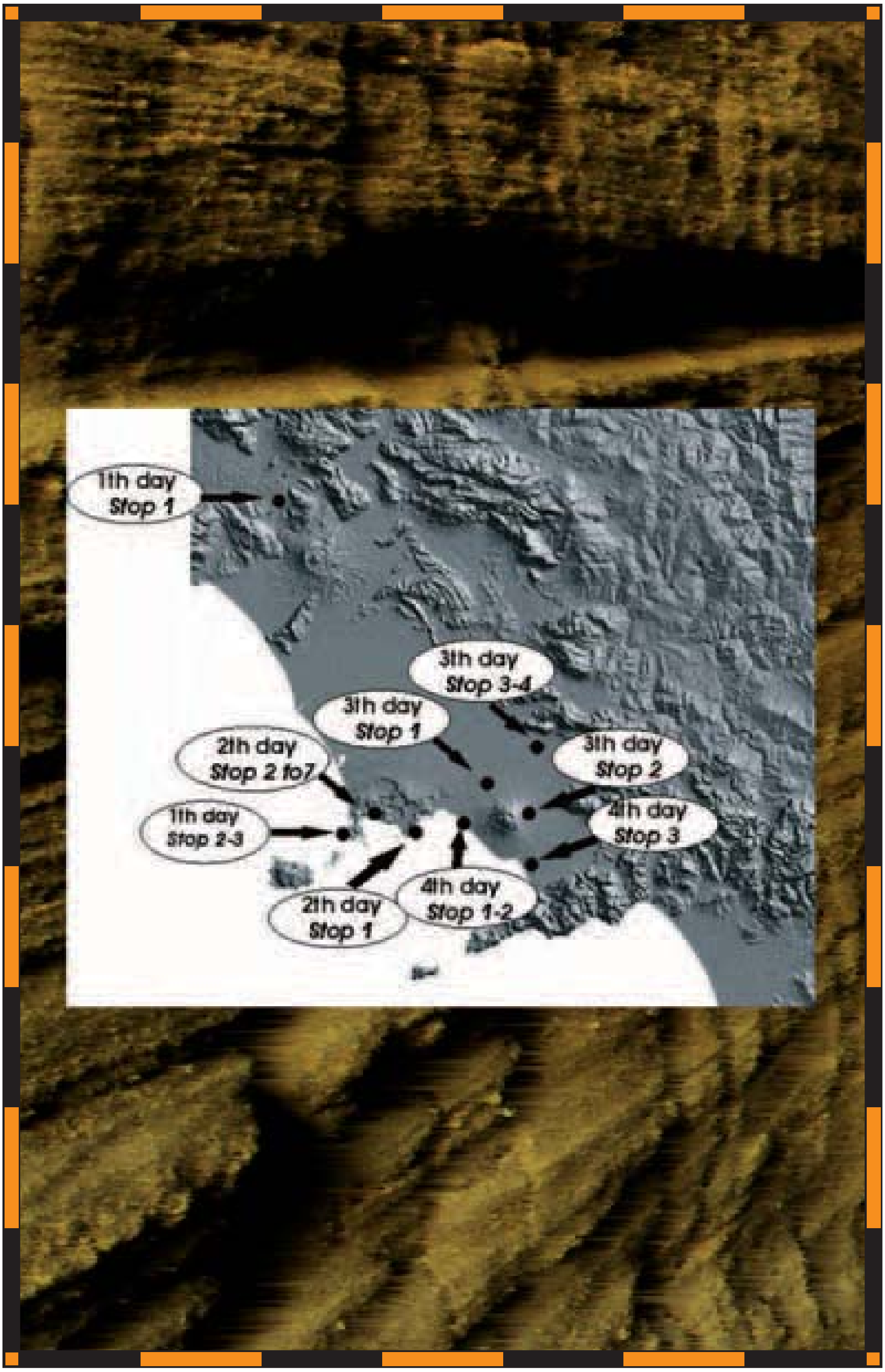
field trip itinerary

32nd INTERNATIONAL GEOLOGICAL CONGRESS

FIELD TRIP MAP



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