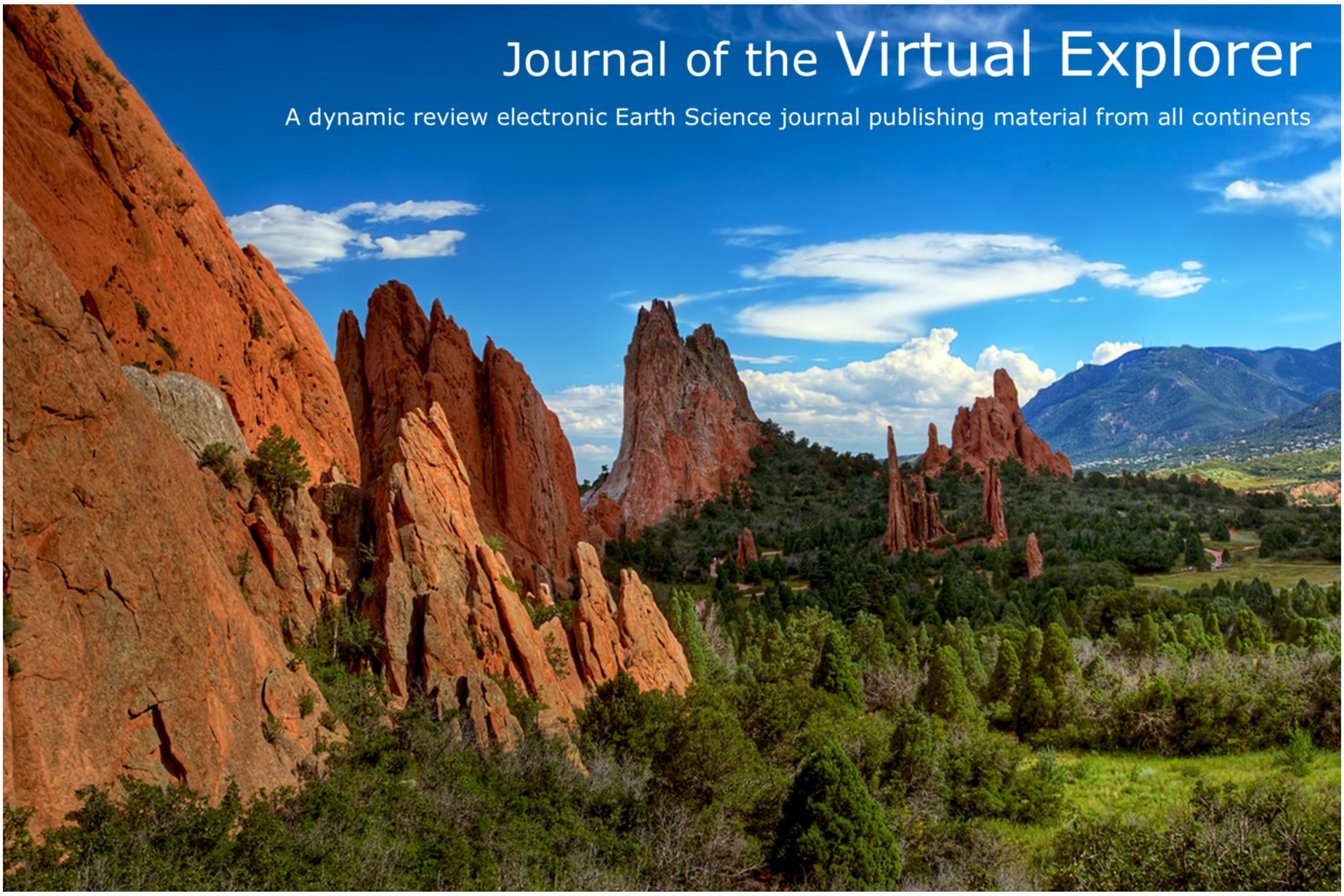

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Urban geology: relationships between geological setting and architectural heritage of the Neapolitan area

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Abstract: The geological setting of the Neapolitan area, dominated by the volcanic districts of Campi Flegrei and Somma-Vesuvius, has played a fundamental role in the urban development since historical times. The volcanic materials emplaced by the two districts have been widely used in the Neapolitan architecture - as dimension stones, building stones and for the production of plasters - due to their great availability and overall good physic-technical properties. While the particular geology of the area has many positive aspects, it nonetheless includes several geo-hazards which have also had a deep influence on the historical evolution of the urban settlements. The numerous aspects of such a link between geology and anthropic activities in the Neapolitan area are here thoroughly investigated.

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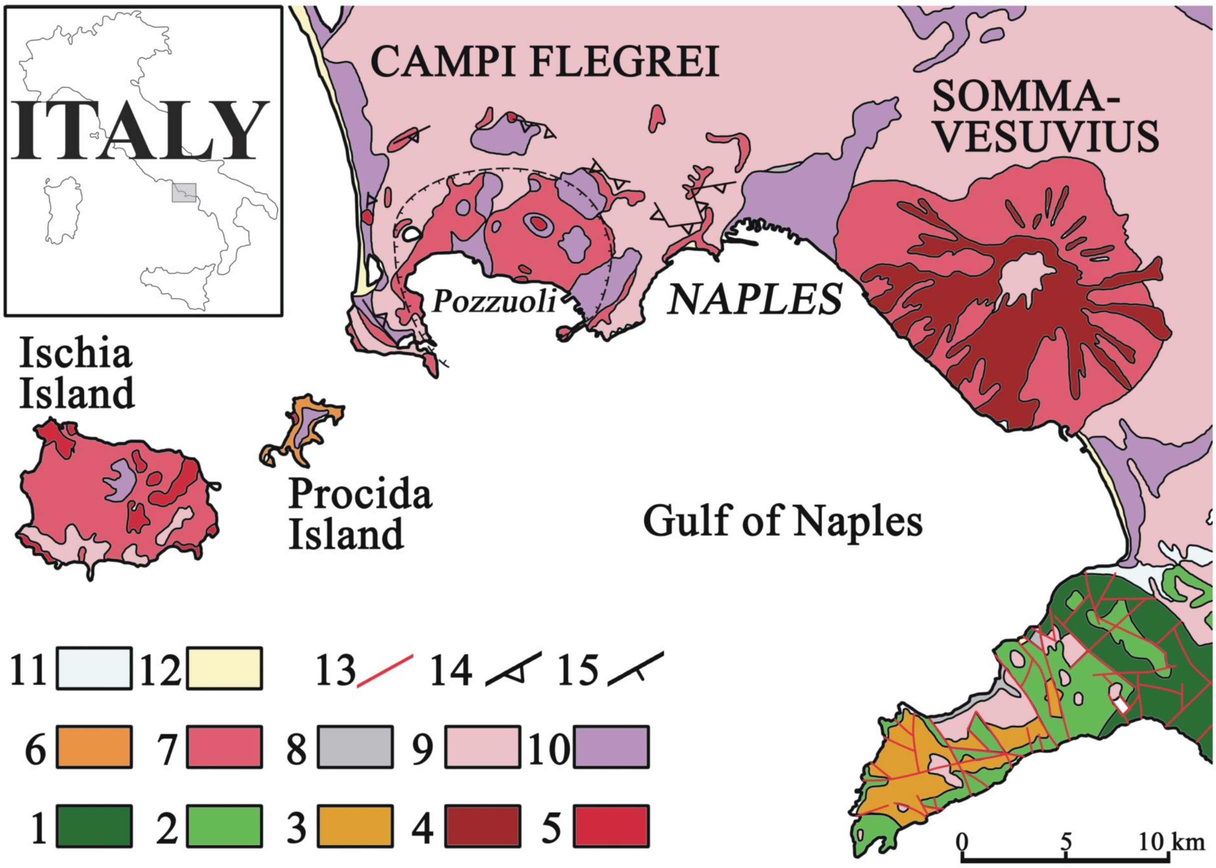
Introduction

As many other cities of art, Naples and its surrounding areas show a strong connection between field geology and architecture. Rocks outcropping in the area were widely used for building purposes so that a sort of specific local "urban colouring" can be recognized as a function of the geomaterials used in the construction of buildings and monuments. Just like the white of travertine for Rome, the grey of the so-called "pietra serena" for Florence and the red of bricks made of local clays for Siena, the dark grey colour of Piperno (usually combined with the yellow of the Neapolitan Yellow Tuff) gave an unmistakable imprint not just to the city of Naples but also to its neigbours of Pozzuoli, Aversa and Portici.

Figure 1. Geology of the Neapolitan area.



Geological sketch map of the Campanian area with the location of the Campi Flegrei and the Somma-Vesuvius districts [modified from Bonardi *et al.* (1988)]. 1) Lower Cretaceous-Liassic carbonate platform deposits; 2) Upper Cretaceous rudistic limestones; 3) Serravallian-Upper Langhian pre- to late orogenic silicoclastic and carbonatic deposits; 4) ultrapotassic lavas (leucitic-basanite and leucititic series); 5) potassic lavas (shoshonitic series); 6) hyalotuffs; 7) pyroclastic flows and surges; 8) Campanian Ignimbrite pyroclastic deposits; 9) pyroclastic fall deposits; 10) volcano-sedimentary deposits; 11) Upper Pleistocene talus breccias; 12) Holocene beach and coastal dunes; 13) faults; 14) boundary of the CI caldera [according to Perrotta *et al.* (2006)]; 15) boundary of the NYT caldera [according to Scarpati *et al.* (1993)].

The geological setting of the territory, along with the widespread occurrence of volcanic and pyroclastic materials in the whole Neapolitan province, strongly conditioned the architecture of Naples and the minor centres since historical times. The sources of these materials are represented by the Campi Flegrei volcanic field and the Somma-Vesuvius complex, two still active volcanic districts belonging to the so-called Plio-Pleistocene "Italian Potassic Magmatism". In particular, the Phlegrean products, due to their abundance and their good workability, as well as their good physical and technical properties, played a significant role in the Neapolitan architecture throughout history. In fact, tuffs have been mainly exploited for the production of dimension stones and also widely used as fine aggregates mixed with pozzolana and lime for the production of the famous Roman plasters. Piperno, to a more limited extent, definitely represents the most significant building stone of the Neapolitan architecture, due to its excellent physico-mechanical features and, above all, for its typical pattern which made it the most used decorative stone between the 18th century and the World War II. Notwithstanding their limited availability, Phlegrean lavas were mainly exploited as road paving blocks and, subordinately, as architectural elements such as columns and building basal elements. Since the 18th century these two stones were progressively replaced by the Vesuvian lavas which were intensively exploited until the 1970s and 80s.

If the local geological setting has represented for Naples and the neighbouring towns a resource and a “positive” value, at the same time it can not be denied that various geohazards threaten the area: volcanic eruptions, landslides, cavity-related surface effects, all connected to the geological and geomorphologic setting. Urban settlements, in fact, rest on a subsoil made of loose and welded pyroclastic deposits, and are located, as previously stated, between the two active volcanic districts of Campi Flegrei and Somma-Vesuvius. In addition, the towns are only a few tens of km from the Apennine chain, where several seismogenetic faults are present. Minor effects can also be caused by coastal erosion, bradiseism and flood events. From a geomorphologic standpoint, the towns of the area are characterised by a hilly landscape, carved in the volcanic products cited above. Such hills, partly “conquered” by man in historical times, have been intensely urbanised since World War II, when some urban districts started to develop both at the top and at the foot of the major hills. Urban growth has increased the risk to some hazards including movement in both lithified and loose pyroclastics (falls, topples, slides, flows).

In addition, due to the good engineering properties of local geological materials (mainly the “pozzolane” and Neapolitan Yellow Tuff), the urban subsoil has been characterized by open-pit and underground quarrying activity since pre-historical times. Underground, instabilities are frequent, causing related damage to the overlying buildings and, sometimes, to humans (15 in two episodes occurred in 1996).

The aim of this paper is to give an exhaustive portrait of the several points of contact between the geological and urban settings of a heavily populated area such as Naples and its surroundings, demonstrating how the evolution of the city has been and still is so deeply and indissolubly influenced by the numerous environmental factors governing the evolution of the territory.

Geological outline

The Campi Flegrei volcanic field and the Somma-Vesuvius complex are two still active volcanic districts belonging to the so-called Plio-Pleistocene “Italian Potassic Magmatism” (e.g., Appleton, 1972; Beccaluva *et al.* 1991; Conticelli *et al.*, 2002, 2004; Peccerillo, 2005). Volcanic activity was related to a very complex geodynamic scenario, dominated by the opening of the Tyrrhenian basin and to the build-up of the Apennine-Maghrebides chain (e.g., Peccerillo e Manetti, 1985; Di Girolamo *et al.*, 1988; Di Girolamo and Morra, 1988; Beccaluva *et al.*, 1991; Doglioni *et al.*, 1997; Gueguen *et al.*, 1998; Lustrino, 2000; Faccenna *et al.*, 2004; Garzanti and Malusà, 2008). Several discussions have been very active in the past regarding the “anorogenic” versus “orogenic” nature of this magmatism, while at the present its “orogenic” character seems to be widely accepted (e.g., Savelli, 2000, 2002; Conticelli *et al.*, 2002; 2004; Mattei *et al.*, 2004, Peccerillo 2005; Peccerillo and Lustrino, 2005).

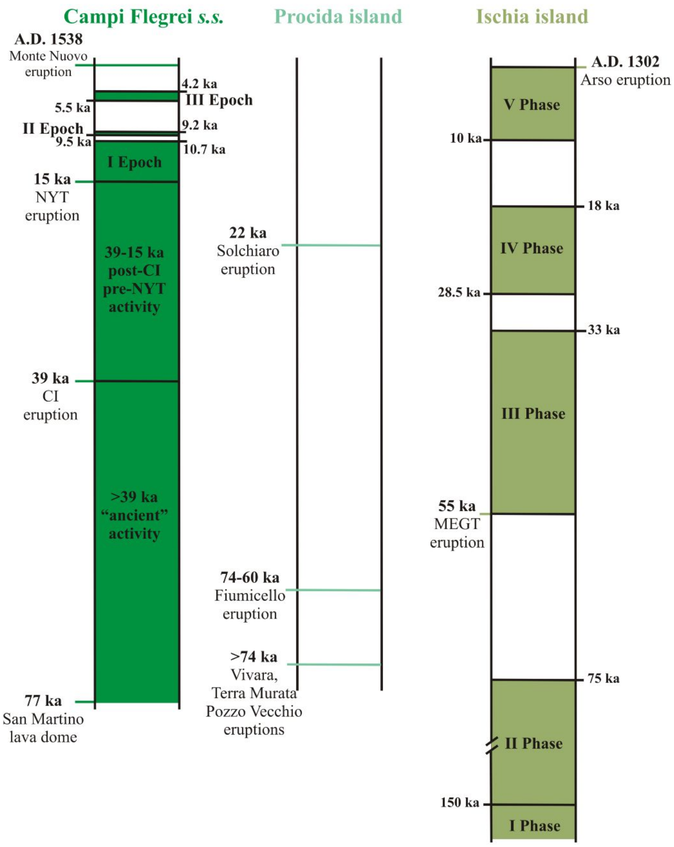
Italian magmatism developed in several volcanic districts, mainly dislocated in a very narrow area in central-southern Italy. Magmatism was mainly effusive, with products showing a serial character ranging from calcalkaline to potassic alkaline to ultrapotassic (e.g., Conticelli *et al.*, 2002, 2004; Peccerillo, 2005). Campanian volcanism is only a small part of the wider Roman Province (including all the volcanic provinces of Latium and Campania; Conticelli *et al.*, 2004). It is to note, however, that some authors have argued that geochemical and isotopic evidences seem to indicate that Campanian volcanites are more akin to the products of the potassic series of Stromboli (Aeolian arc), rather than to the products of the other districts of the Roman Province (e.g., Peccerillo, 2001, 2005). Campanian volcanic products essentially show two different serial affinities, namely a potassium (shoshonitic) series and a high potassium series (respectively, KS and HKS), with products of the two series being very recurrently found together in the same volcanic district (e.g., at the Roccamonfina and the Somma-Vesuvius volcanic complexes; Conticelli *et al.*, 2002, 2004). Rocks belonging to the KS are represented by saturated to slightly undersaturated products, with K_2O/Na_2O approaching unity. Compositions range from shoshonitic basalt, through shoshonite and latite to trachyte. The HKS is made of ultrapotassic, mildly to strongly Si-undersaturated leucite-bearing products, whose composition range from leucitite and basanite through leucite tephrite, leucite tephriphonolite to phonolite (e.g., Conticelli *et al.*, 2002, 2004; Peccerillo, 2005).

Several studies have been published on the nature of the mantle sources of the whole Italian potassic province (e.g., Vollmer, 1977; Hawkesworth and Vollmer, 1979; Beccaluva *et al.*, 1991; Conticelli *et al.*, 2002, 2004; Peccerillo, 2005), as well as on the sources of the rocks of the Campanian region (e.g., D'Antonio and Di Girolamo, 1994; D'Antonio *et al.*, 1996, 1999a, 2007; Piochi *et al.*, 2004). Many of them evidenced the existence of a great variability of K_2O and incompatible element contents, coupled with a similar variability of Sr, Nd and Pb isotope ratios, usually considered to be related to crustal assimilation and source contamination processes. The most recent models (e.g., Conticelli *et al.*, 2002, 2004; Peccerillo, 2005) argue for a very complex source for the Campanian rocks, made of several different components, including subducted continental crust, depleted MORB-mantle and HIMU components. The various degree of Si-undersaturation of the products is probably reflecting a different residual character of the involved sources (lherzolitic for the more undersaturated and harzburgitic for the more saturated ones), coupled with variable metasomatization and partecipation of the metasomatic phases in the melting processes.

The Campi Flegrei

The Campi Flegrei is a volcanic field located immediately west of the city of Naples (Fig. 1). Its volcanic history was characterized by a great number of eruptions, giving birth to mainly monogenetic edifices and emplacing huge volumes of pyroclastic rocks and very sporadic small-scale lava flows. Phlegrean volcanism includes not only the activity developed on the continent (the Campi Flegrei *strictu sensu*) but also the activity developed on the islands of Ischia and Procida, which share many geological, volcanological, petrochemical and petrological similarities with Campi Flegrei *s.s.* (Di Girolamo *et al.*, 1984, 1995; De Astis *et al.*, 2004).

Figure 2. Geochronology of Campi Flegrei eruptions.



Chronological sketches summarizing the periods of active volcanism in the continental (i.e., Campi Flegrei strictu sensu) and insular (Procida and Ischia islands) portions of the Campi Flegrei district. White areas represent known periods of volcanic quiescence, while coloured areas represent periods of active volcanism (with coloured thick marks corresponding to particularly significative volcanic events). See text for a more detailed treatment.

The beginning of Phlegrean volcanism is not yet well constrained. Di Girolamo *et al.* (1976, 1996) and Barbieri *et al.* (1979) reported the occurrence in some exploratory wells drilled in the Campanian Plain of calcalkaline volcanics (lavas and volcanoclastites) dating back to ~2.0 Ma and tentatively related them to the very first manifestations of magmatism in the Campanian region related to build-up of the Apennine chain. De Vivo *et al.* (2001) suggested that Campi Flegrei volcanism began at least ~315 ka, on the basis of geochronological data on previously unrecognized pyroclastic deposits outcropping in the peripheral portions of the Campanian Plain. Not taking into account these poorly studied and constrained deposits, it should be noted that insular volcanism has been historically retained to largely predate continental one. More specifically, the oldest outcropping products of the entire Phlegrean area were commonly thought to be those marking the base of the volcanic sequence at Ischia, dating back to more than 150 ka (Poli *et al.*, 1987; Vezzoli, 1988).

The volcanic history of the Ischia island is generally subdivided into five phases (Vezzoli, 1988; Fig. 2):

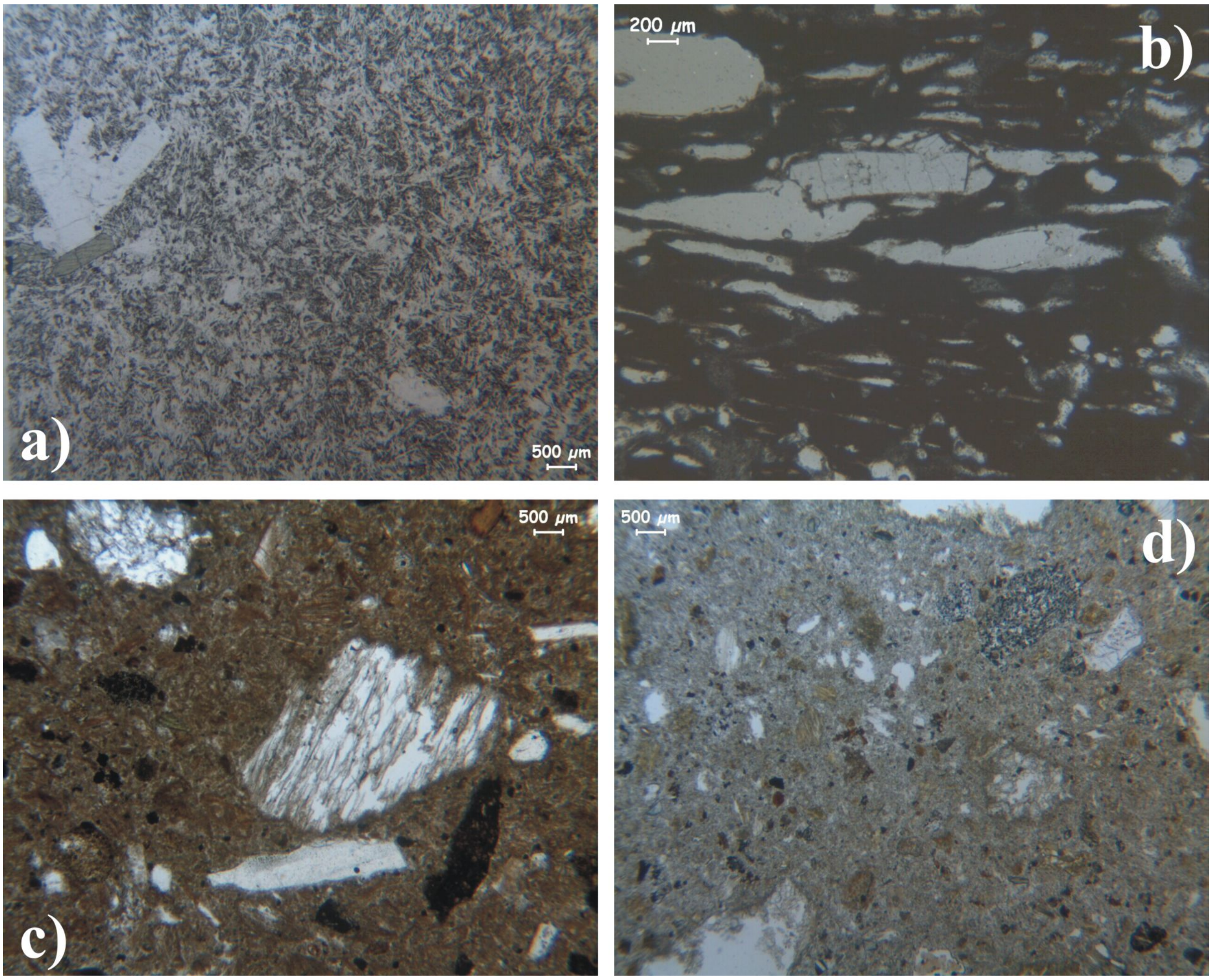
- 1st phase (>150 ka). The pyroclastic deposits of this phase belong to an ancient volcanic complex, probably covering a wider area with respect to the present island and now almost completely destroyed. Volcanic activity was mainly represented by very energetic pyroclastic eruptions. The observation of two well-developed humified horizons suggests the occurrence of at least two long repose periods (Poli *et al.*, 1987).
- 2nd phase (150-75 ka). Lava eruptions are the main feature of this phase. The distribution of lava domes indicates a sub-circular structure along the south-western and south-eastern sides, possibly suggesting the presence of a caldera rim with a large depression at the center of the island.
- 3rd phase (55-33 ka). After ~20 kyrs of quiescence, a new phase of activity occurred, starting with the Monte Epomeo Green Tuff (MEGT, ~55 ka, K/Ar; Vezzoli, 1988) eruption, the most powerful volcanic event on the island. The deposits of this event show the typical ignimbritic welded facies (with abundant pumices, lithics and biotite and K-feldspar loose crystals) only in correspondence of the Monte Epomeo volcano-tectonic horst. The characteristic greenish colour is due to sea-water alteration of the vitric ignimbrite matrix in hydrothermal conditions. Other facies include non-welded ash flow and pumice flow deposits and alternances of pyroclastic flow deposits with an explosive breccia at the bottom (Vezzoli, 1988).
- 4th phase (28.5-18 ka). Volcanism is concentrated in the south-western sector of the island, probably related to the reactivation of the NE-SW fault system corresponding to the volcanic alignment of Ischia, Procida and continental Campi Flegrei.
- 5th phase (10 ka-A.D. 1302). After a new period of quiescence (~10 kyrs), a new reprise of volcanism occurred, mainly involving the eastern sector of the island, corresponding to the Ischia Graben area (Vezzoli, 1988) and possibly related to the resurgence of the Monte Epomeo block (Orsi *et al.*, 1991). This last phase was almost exclusively characterized by volcanic eruptions coming from monogenetic vents, and is closed by the A.D. 1302 historical eruption of Arso (Gasparini and Adams, 1969; Gillot et al, 1982; Vezzoli, 1988; Civetta *et al.*, 1991c).

The onset of volcanism on Procida island is generally thought to post-date Ischia's oldest activity (i.e., the first two phases). The oldest products occurring on the island are represented by the pyroclastic deposits which built the Pozzo Vecchio, Vivara and Terra Murata volcanoes (Rosi *et al.*, 1988; De Astis *et al.*, 2004; Fedele *et al.*, in press), which must be collocated somewhere before 74 ka, given their occurrence in lower stratigraphic position with respect to the deposits of the Pignatiello formation of Ischia (dated between 55 and 74 ka; Vezzoli, 1988). The pyroclastic products of the youngest edifices of Fiumicello (60-74 ka; Fedele *et al.*, in press) and Solchiaro (~17-19 ka, ^{14}C ages; Alessio *et al.*, 1976; Lirer *et al.*, 1991; calibrated to 22 ka by Fedele *et al.*, in press) are the only other deposits clearly ascribable to Procida volcanism. A single effusive event is recorded on the island, represented by emission of the Punta Ottimo lava dome (Di Girolamo and Stanzione, 1973; Di Girolamo *et al.*, 1984; De Astis *et al.*, 2004; Fedele *et al.*, in press).

As regards the continental portion of the Campi Flegrei, the first volcanic manifestations seem to be even younger with respect to Procida oldest activity. The products of the Punta Marmolite and Cuma lava domes (respectively ~47 and ~37 ka, K/Ar ages; Cassignol and Gillot, 1982) and of the Tufi di Torre Franco formation (~42 ka, ^{14}C; Alessio *et al.*, 1973) have been historically considered to represent the oldest products of Campi Flegrei *s.s.* activity. Recent datings have brought the lower age limit of continental activity progressively backwards, firstly to 58 ka (^{40}Ar/^{39}Ar; Pappalardo *et al.*, 1999) and then up to ~77 ka (^{40}Ar/^{39}Ar of the San Martino lava dome, Fig. 3a; Fedele *et al.*, in press).

Volcanism at Campi Flegrei *s.s.* has been variously subdivided into distinct periods of activity (e.g., De Lorenzo, 1904, Rittmann, 1950; Di Girolamo *et al.*, 1984; Rosi and Sbrana, 1987). Notwithstanding the differences between them, these schematizations are fundamentally based on the identification of two major volcanic events, whose deposits have always been used as efficient stratigraphic markers.

Figure 3. Petrography of Campi Flegrei rocks.



Microphotographs of some representative Campi Flegrei products: a) plane polarized view of a trachytic lava from the San Martino lava dome showing a weakly porphyritic texture with phenocrysts of sanidine and clinopyroxene (left side) set into a groundmass predominantly made by sanidine microcrysts; b) plane polarized view of the trachytic welded tuff from the Piperno unit showing the typical eutaxitic texture with iso-oriented collapsed scoriae (*fiammae*) set into a cineritic matrix (in the center of the picture a sanidine phenocryst is also visible); c) plane polarized view of a trachytic tuff of the CI formation [belonging to the WGI unit of Cappelletti *et al.* (2003)] showing pumices, lava lithic fragments, sanidine, clinopyroxene and biotite (upper side of the picture) loose crystals set into abundant ashy matrix; d) plane polarized view of a trachytic tuff of the NYT formation showing pumices and lava lithics plus minor sanidine and clinopyroxene loose crystals set into an ashy matrix.

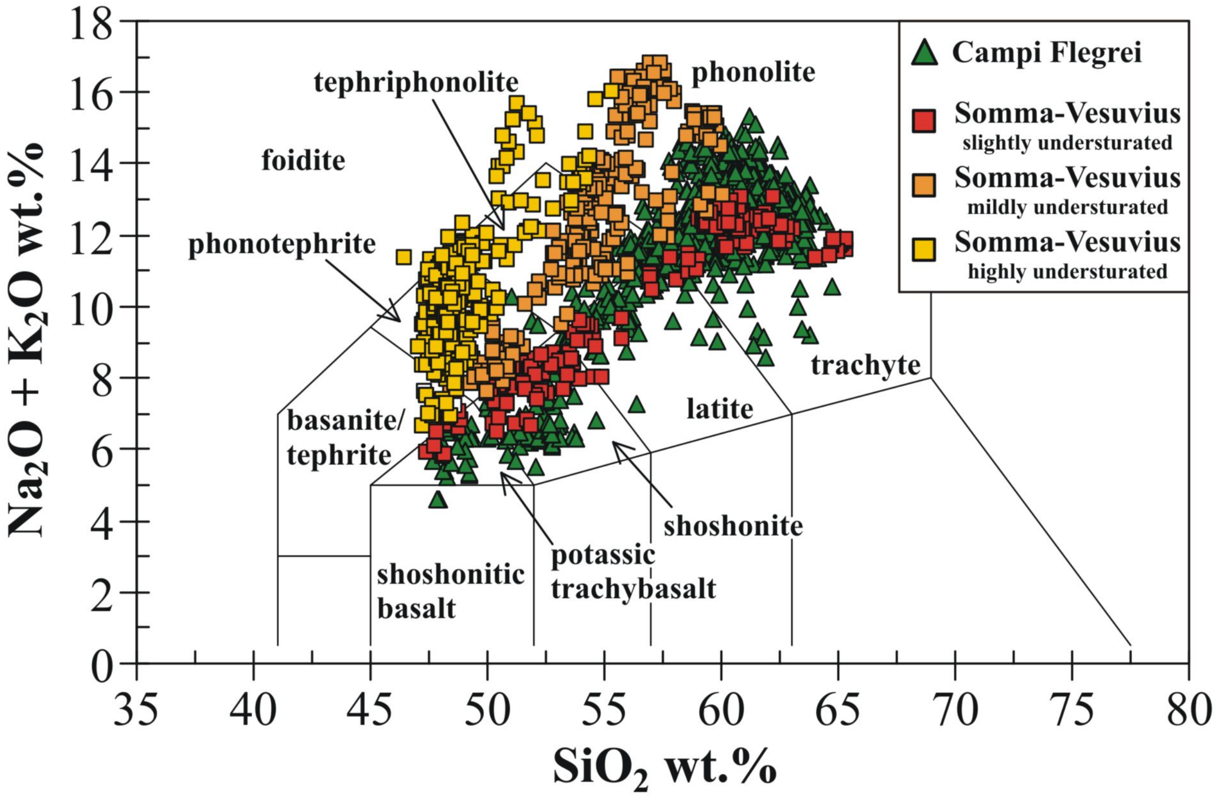
The first is the Campanian Ignimbrite (hereafter CI) eruption, the most powerful event ever occurred in the Mediterranean area in the last 200 ka (Barberi *et al.*, 1978). The eruption, occurred ~39 ka (^{40}Ar/^{39}Ar; Deino *et al.*, 1994; De Vivo *et al.*, 2001; Ricci, 2000), was probably accompanied by an extensive caldera collapse, which gave birth to the Campi Flegrei caldera (e.g., Rittmann, 1950; Rosi *et al.*, 1983; Rosi and Sbrana, 1987; Orsi *et al.*, 1996; Perrotta *et al.*, 2006). The CI eruption emplaced a widespread pyroclastic fall and flow sequence, basically of trachytic composition (plus rarer phonolites), covering an area from the Campi Flegrei district to as far away as the eastern Mediterranean Sea and Russia (Barberi *et al.* 1978; Thunnel *et al.*, 1979; Sparks and Huang, 1980; Cornell *et al.*, 1983; Rosi and Sbrana, 1987; Scandone *et al.*, 1991; Fedele *et al.*, 2002; Wulf *et al.*, 2004; Perrotta *et al.*, 2006; Pyle *et al.*, 2006). Proximal deposits, preserved in limited outcrops along the Campi Flegrei caldera rim, constitute a complex sequence of six units (the so-called “Breccia Museo”) consisting mainly of coarse, lithic-breccia and welded horizons (Rosi and Sbrana, 1987; Perrotta and Scarpati, 1994; Melluso *et al.*, 1995; Rosi *et al.*, 1996; Perrotta *et al.*, 2006; Fedele *et al.*, 2008). One of the most particular volcanic units of the proximal sequence is represented by the so-called “Piperno” (e.g., De Lorenzo, 1904; Rittmann, 1950; Perrotta and Scarpati, 1994; Rosi *et al.*, 1996; Perrotta *et al.*, 2006; Fedele *et al.*, 2008), a deposit made of alternating beds of welded ash with flattened scoriae (*fiammae*), resulting in the typical eutaxitic texture (Fig. 3b), and a monolithologic coarse breccia made up of grey lava fragments, exposed exclusively in the eastern sector of Campi Flegrei and in the city of Naples and widely used as a building stone (see following sections).

Deposits of the CI found in medial exposures (i.e., the Campanian Plain and the Apennine chain, up to 80 km from the vent area) consist mainly of a stratified plinian pumice deposit overlain by a grey welded tuff [the WGI unit of Cappelletti *et al.* (2003); Fig. 3c] that grades upwards into a yellow one [the LYT unit of Cappelletti *et al.* (2003); see also Fisher *et al.* (1993), Rosi *et al.* (1999), Perrotta and Scarpati (2003)]. The type-sequence is completed by a basal stratified, incoherent ash to sandy deposit and a topmost incoherent coarse pumice deposit with an ashy matrix [respectively, USAF and CPF, Cappelletti *et al.* (2003)]. Finally, in distal areas CI deposits have been correlated to a stratified ash layer identified in eastern Europe (Sparks and Huang, 1980; Cornell *et al.*, 1983). The volume of the ignimbrite is not well constrained, and proposed estimates range from 80 to 500 km^3 (e.g., Barberi *et al.*, 1978; Thunnel *et al.*, 1979; Fisher *et al.*, 1993).

The second most explosive event of Campi Flegrei history is the Neapolitan Yellow Tuff (NYT) eruption, for which ^{40}Ar/^{39}Ar datings indicate an age of ~15 ka (^{40}Ar/^{39}Ar; Deino *et al.*, 2004; Insinga *et al.*, 2004). The eruption, accompanied by a second caldera collapse episode (Di Girolamo *et al.*, 1984; Orsi *et al.*, 1992a, 1996; Scarpati *et al.*, 1993), emplaced a deposit mainly consisting of two distinctive members: member A, a succession of cineritic and pumiceous lapilli layers, and member B, a deposit made of cineritic layers with dispersed rounded pumices (Scarpati *et al.*, 1993). The deposits of the latter member, constituting the great part of the entire erupted sequence, occur as a yellowish massive lithified tuff (the so-called “*Tufo*”; Fig. 3d) in the proximal areas, as an unlithified light grey pumiceous cinerite (“*Pozzolana*”) in the more distal exposures (e.g., Di Girolamo *et al.*, 1984; Rosi and Sbrana, 1987; Orsi *et al.*, 1991, 1992a; Cole and Scarpati, 1993; Scarpati *et al.*, 1993; Wholetz *et al.*, 1995; Valentini *et al.*, 2008). The emplaced products, ranging in composition from latite to trachyte, cover an estimated area of ~1000 km^2 (Wholetz *et al.*, 1995), reaching a total dense rock equivalent volume of ~50 km^3 (Scarpati *et al.*, 1993).

Campi Flegrei volcanic activity postdating NYT eruption, generally referred to as the “recent” phase, is concentrated well within the boundary of the NYT caldera. Such phase of volcanism has been very deeply studied in the last 20-25 years, allowing to depict a very detailed reconstruction of the chronology of the numerous events occurred. The reason for this is twofold. On one hand, a detailed knowledge of the recent behaviour of the Campi Flegrei is necessary for a correct evaluation of the volcanic hazard (and, consequently, of the volcanic risk) related to the district. Moreover, the two caldera collapses created favourable outcropping conditions for the youngest deposits (while, on the contrary, much of the deposits emplaced before one or both the collapses are presently very hard to be recovered due to their sinking and their burial beneath the products of the recent activity). According to Di Vito *et al.* (1999a) and Orsi *et al.* (2004), Campi Flegrei recent volcanism can be subdivided in three epochs of activity, identificated on the basis of the recognition of three periods of volcanic quiescence. The first epoch goes from 15 ka (i.e., age of the NYT eruption) to 9.5 ka [^{14}C age, recalibrated to ~10.7 ka by Fedele *et al.* (2009a)] and is characterized by at least 37 explosive events (with magmatic to phreatomagmatic eruptive style), the most energetic of which is the Pomici Principali eruption (Astroni volcano; Rittmann, 1950; Di Girolamo *et al.*, 1984; Rosi and Sbrana, 1987; Lirer *et al.*, 1987a; Di Vito *et al.*, 1999a), for which Di Vito *et al.* (1999a) obtained a ^{14}C age of ~10.3 ka [recalibrated at ~12.2 ka by Fedele *et al.* (2009a)]. This epoch is followed by a period of quiescence, testified by the development of a thick paleosoil horizon extensively recognized by the authors throughout the Phlegrean district. The second epoch goes from 8.6 to 8.2 ka [^{14}C ages of Di Vito *et al.* (1999a), recalibrated respectively to ~9.5 and ~9.2 ka by Fedele *et al.* (2009a)] and is characterized by only 6 episodes of low volcanic magnitude which mainly concentrated in the north-eastern sector of the district. After a new period of prolonged volcanic quiescence, a new epoch of activity began, spanning the time interval between 4.8 and 3.8 ka [^{14}C ages of Di Vito *et al.* (1999a), recalibrated respectively to ~5.5 and ~4.2 ka by Fedele *et al.* (2009a)]. This phase was characterized by 20 explosive and 3 effusive events (generally concentrated along fault zones running along the north-western border of the NYT caldera; Orsi *et al.*, 1996), the most powerful of which was the Agnano-Monte Spina eruption (4.1 ka, ^{40}Ar/^{39}Ar age; de Vita *et al.*, 1999). The end of the third epoch is marked by a new phase of quiescence, interrupted by the A.D. 1538 Monte Nuovo historical eruption (Di Vito *et al.*, 1987; Lirer *et al.*, 1987b; D'Oriano *et al.*, 2005; Piochi *et al.*, 2005). It is worth of note that the above schematization of Campi Flegrei recent activity, although very detailed and based on a notable wealth of data, seems to need further reworking in the light of recent absolute datings (e.g., Insinga *et al.*, 2006; Fedele *et al.*, 2009a), which collocate some eruptive events into periods formerly retained of volcanic quiescence.

Figure 4. Classification of Campi Flegrei and Somma-Vesuvius rocks.



Total-Alkali vs. Silica classification diagram (Le Bas *et al.*, 1986) for Campi Flegrei and Somma-Vesuvius rocks from the existing literature data [Campi Flegrei: Albini *et al.* (1977), Armienti *et al.* (1983), Barberi *et al.* (1978), Beccaluva *et al.* (1991), Bohrson *et al.* (2006), Carbone *et al.* (1984), Civetta *et al.* (1988, 1991a, 1997), Crisci *et al.* (1989), D'Antonio and Di Girolamo (1994), D'Antonio *et al.* (1996, 1999a, 1999b, 2007), De Astis *et al.* (2004), de Vita *et al.* (1999), Di Girolamo (1968, 1970), Di Girolamo *et al.* (1973, 1984, 1995), Di Girolamo and Stanzione (1973), Di Girolamo and Rolandi (1979), D'Oriano *et al.* (2005), Fedele (2006), Fedele *et al.* (2006, 2008), Fowler *et al.* (2007), Ghiara (1989-1990), Ghiara *et al.* (1977, 1979), Insinga (2004), Lirer *et al.* (1987a), Lustrino *et al.* (2002), Melluso *et al.* (1995), Orsi *et al.* (1992a, 1992b, 1995), Pappalardo *et al.* (1999, 2002a, 2002b), Piochi *et al.* (1999), Poli *et al.* (1987), Rosi and Sbrana (1987), Scarpati *et al.* (1993), Signorelli *et al.* (1999a), Vezzoli (1988), Villemant (1988); Somma-Vesuvius: Aulinas *et al.*, 2007; Ayuso *et al.* (1998), Barberi *et al.* (1981), Black *et al.* (1998), Brocchini *et al.* (2001), Cioni *et al.* (1992, 1995, 1998, 2003), Civetta and Santacroce (1992), Civetta *et al.* (1991b, 2004). Cortini and Hermes (1981), Cortini *et al.* (2004), Di Renzo *et al.* (2007), Di Vito *et al.* (1999b), Fulignati *et al.* (2000), Landi *et al.* (1999), Marianelli *et al.* (1999), Piochi *et al.* (2006), Rolandi *et al.* (2004b), Rosi and Santacroce (1983), Santacroce (1987), Santacroce *et al.* (1993), Savelli (1967a), Signorelli *et al.* (1999b)].

At present, Campi Flegrei activity is mainly fumarolic and hydrothermal, with sporadic bradiseismic episodes, like those of the 1969-1972 and 1982-1984 crises, during which a total round uplift of 3.5 m was recorded near the town of Pozzuoli (Barberi *et al.*, 1991).

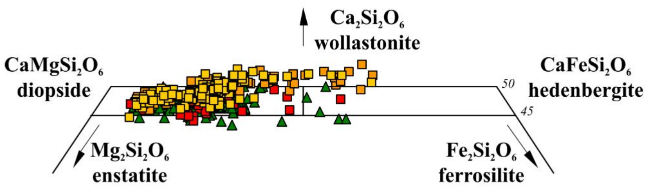
Campi Flegrei rocks range in composition from potassic alkaline basalt ("shoshonitic basalt") to trachyte and phonolite, defining a typical potassium alkaline "shoshonitic" series. The most differentiated products, and particularly the trachytes, are by far the dominant lithotypes (Fig. 4), whereas the less evolved shoshonitic basalts and shoshonites are sensitively rarer, being almost exclusively represented by the products of Procida island. Rock textures vary from totally aphyric to slightly porphyritic (up to ~30% of phenocrysts). The most abundant mineral phases are represented by clinopyroxene, plagioclase, sanidine, biotite and magnetite. Olivine is confined to the least evolved lithotypes (from shoshonitic basalts to latites). Common accessory phases are apatite and zircon, while brown amphibole, titanite (particularly in Ischia products) and feldspathoids (usually nepheline) have been found only in the most differentiated products. Sodalite, aegirine and aegirine-augite have been sporadically observed in the most evolved trachytes of Ischia (Crisci *et al.*, 1989).

Chemical composition of the main mineral phases can be briefly summarized as follows.

Olivine. Olivine crystals, typically confined to the very few least differentiated rocks, show very narrow compositional ranges, spanning from Fo_{88} to Fo_{80}. A sensitively wider spectrum has been reported for olivine crystals from Ischia products, ranging from Fo_{89} to Fo_{72} (Crisci *et al.*, 1989; Di Girolamo *et al.*, 1995; Piochi *et al.*, 1999). Phenocrysts are usually altered to iddingsite (Armienti *et al.*, 1983) and contain Mg-Cr spinel inclusions (D'Antonio and Di Girolamo, 1994).

Clinopyroxene. Clinopyroxene is the dominant phenocryst in the least differentiated rocks, while its abundance in the more differentiated products is inversely proportional to the degree of evolution. Clinopyroxene from the least differentiated volcanics is pale green to greenish, ranging from Mg-rich diopside to Fe-rich diopside, commonly showing both normal and reverse zoning (Beccaluva *et al.*, 1990; D'Antonio and Di Girolamo, 1994). In latites and trachytes two clinopyroxenes typically occur: a greenish salitic one and a colourless diopsidic, with the latter being generally less abundant. Chemical compositions are fairly homogeneous (from $Ca_{47}Mg_{40}Fe_{13}$ to $Ca_{47}Mg_{35}Fe_{18}$ for salite and from $Ca_{47}Mg_{49}Fe_{4}$ to $Ca_{47}Mg_{45}Fe_{8}$ for diopside; Vezzoli, 1988; Melluso *et al.*, 1995; Piochi *et al.*, 1999; Ricci, 2000; Fedele *et al.*, 2008, 2009b; Fig. 5). However, zoned crystals also occur, usually showing a diopsidic core rimmed by a salitic border (Civetta *et al.*, 1997; Ricci, 2000; Fedele *et al.*, 2008). Clinopyroxene crystals from Ischia trachytes and phonolites are usually characterized by high aegirine contents (Na_2O up to ~9 wt.%; Poli *et al.*, 1987; Crisci *et al.*, 1989).

Figure 5. Classification of Campi Flegrei and Somma-Vesuvius clinopyroxenes.

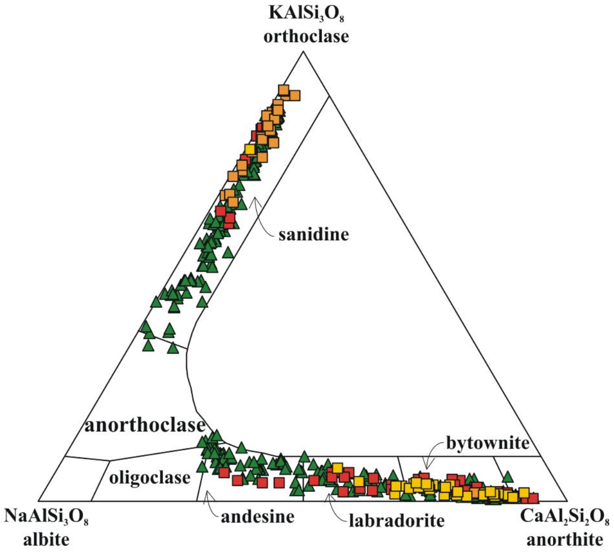


Composition of representative Campi Flegrei and Somma-Vesuvius clinopyroxene crystals from the existing literature data [Campi Flegrei: Armienti *et al.* (1983), Civetta *et al.* (1997), de Vita *et al.* (1999), Di Girolamo *et al.* (1995); Fedele *et al.* (2006, 2008), Fulignati *et al.* (2004), Ghiara *et al.* (1979), Melluso *et al.* (1995), Orsi *et al.* (1995), Pappalardo *et al.* (2002a), Piochi *et al.* (1999), Poli *et al.* (1987), Signorelli *et al.* (1999a); Somma-Vesuvius: Barberi *et al.* (1981), Cioni *et al.* (1995, 1998), Fulignati *et al.* (2000), Marianelli *et al.* (1999), Santacroce (1987), Santacroce *et al.* (1993), Savelli (1967a)] Symbols as in Fig. 4.

Plagioclase. Plagioclase is a very common phase in the least differentiated rocks, being progressively replaced by K-feldspar in the most evolved products. In trachybasalts plagioclase compositions span a very large spectrum, from An_{95} to An_{56} (Armienti *et al.*, 1983; D'Antonio and Di Girolamo, 1994). With the progressive transition to latites and trachytes, Na_2O and K_2O contents tend to constantly increase, leading to andesinic-oligoclasic compositions (from An_{32} to An_{25}; Crisci *et al.*, 1989; Piochi e al., 1999; Fedele *et al.*, 2008; Fig. 6).

K-Feldspar. Sanidine occurs in trachybasalts only as small individuals dispersed in the groundmass, whereas in latites is also present as plagioclase outer rims and in trachytes it represents the absolutely dominant phenocryst phase, accounting for ~90% of the total phenocryst content (Armienti *et al.*, 1983; Civetta *et al.*, 1997). Orthoclase molecula content goes from ~Or_{73} of the least differentiated rocks to ~Or_{87} of trachytes (Fedele *et al.*, 2008) and then decreases to more sodic and calcic compositions up to Or_{63} in the most differentiated phonolites (Armienti *et al.*, 1983; Fig. 6). Very Na_2O-rich varieties have been reported for Ischia trachytes (up to Or_{34}; Crisci *et al.*, 1989; Piochi *et al.*, 1999).

Figure 6. Classification of Campi Flegrei and Somma-Vesuvius feldspars.

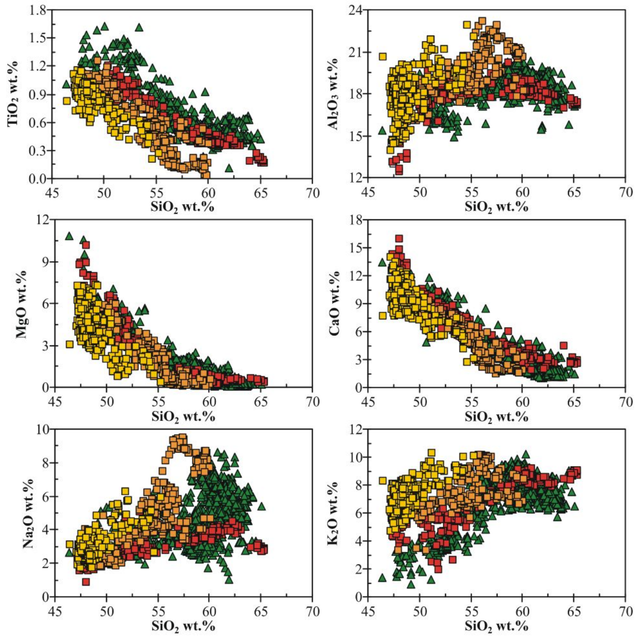


Composition of representative Campi Flegrei and Somma-Vesuvius feldspar crystals from the existing literature data [Campi Flegrei: Armienti *et al.* (1983), Civetta *et al.* (1997), de Vita *et al.* (1999), Di Girolamo *et al.* (1995); Fedele *et al.* (2006, 2008), Fulignati *et al.* (2004), Ghiara *et al.* (1979), Melluso *et al.* (1995), Orsi *et al.* (1995), Pappalardo *et al.* (2002a), Piochi *et al.* (1999), Poli *et al.* (1987), Signorelli *et al.* (1999a); Somma-Vesuvius: Barberi *et al.* (1981), Cioni *et al.* (1995), Landi *et al.* (1999), Santacroce (1987), Santacroce *et al.* (1993),] Symbols as in Fig. 4.

Biotite. Biotite is quite recurrent in Campi Flegrei products, occurring as phenocrysts or microphenocrysts from latites to trachytes and as small groundmass individuals in trachybasalts (Armienti *et al.*, 1983). Crystals are generally unzoned Mg-biotites [according to the nomenclature proposed by Rock, (1982)], usually containing apatite inclusions (Pappalardo *et al.*, 2002a) and showing moderate TiO_2 contents (4.7-4.8 wt.%; Melluso *et al.*, 1995; Fedele *et al.*, 2008). Its occurrence in trachytic products is a clear evidence of very high H_2O.

Opaque oxides. A Ti-magnetite phase is present in Phlegrean rocks as phenocrysts and microphenocrysts, particularly abundant in latites (Armienti *et al.*, 1983). The ulvöspinel content constantly decreases from trachybasalts and latites (~25-28%) to trachytes (~16-20%; Armienti *et al.*, 1983; Melluso *et al.*, 1995; Civetta *et al.*, 1997; Fedele *et al.*, 2008).

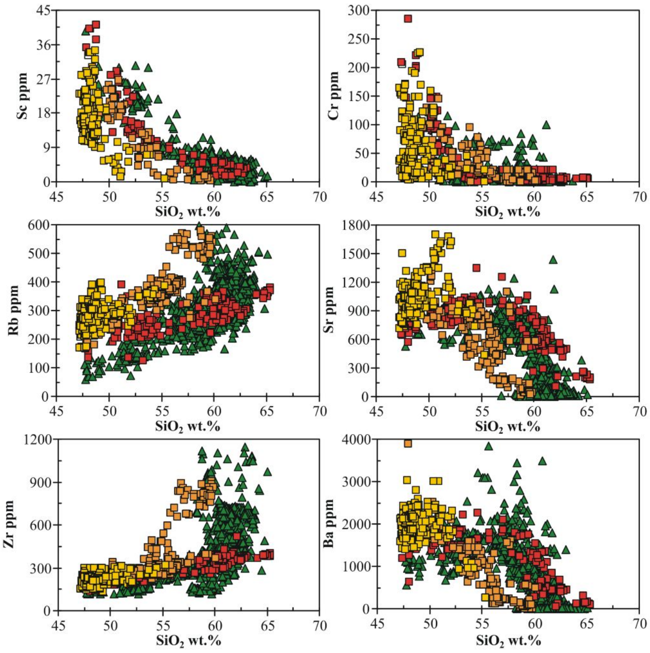
Figure 7. Major elements of Campi Flegrei and Somma-Vesuvius rocks



Selected major element binary diagrams for Campi Flegrei and Somma-Vesuvius rocks from the existing literature data (see Fig. 3 for references). Symbols as in Fig. 4.

Phlegrean volcanites are characterized by low TiO_2, Nb, and Ta, high K_2O and Al_2O_3 and high LILE/HFSE (Large Ion Litophile Elements; High Field Strength Elements) and LREE/HREE ratios (Light Rare Earth Elements; Heavy Rare Earth Elements). With increasing rock differentiation, TiO_2, Fe_2O_3, MgO, CaO and P_2O_5 decrease, SiO_2 and Na_2O increase (Fig. 7). K_2O firstly slightly increases, then, when magmas approach trachytic compositions, it rapidly falls. Among trace elements, LREE, Y, Zr, Nb, Th, Rb and Ta are all strongly incompatible, whereas V, Sc, Ba and Sr show a compatible character (Fig. 8). These variation patterns suggest crystal fractionation of the observed mineral phases, mainly clinopyroxene (CaO, MgO, Fe_2O_3, V and Sc decrease), plagioclase (CaO, Ba and Sr), Fe-Ti oxides (TiO_2, Fe_2O_3, Sc and V) and apatite (P_2O_5). The "bell-shaped" differentiation pattern of K_2O is clearly related to the scarce or even absent sanidine crystallization during the first phases of differentiation (dominated by clinopyroxene and plagioclase), followed by its massive fractionation when magmas reach trachytic compositions and sanidine becomes the main fractionating phase.

Figure 8. Trace elements of Campi Flegrei and Somma-Vesuvius rocks



Selected trace element binary diagrams for Campi Flegrei and Somma-Vesuvius rocks from the existing literatuer data (see Fig. 3 for references). Symbols as in Fig. 4.

Even though overall linear fractionation trends seem to suggest for Campi Flegrei rocks an evolution basically dominated by closed-system fractional crystallization, many authors have reported several lines of petrographic, geochemical and isotopic evidences in favour of a possible role (though limited) of open-system processes, such as mixing and/or mingling of different magma batches, magma contamination by hydrothermal fluids, wall-rock assimilation (e.g., Cortini and Hermes, 1981; Vollmer *et al.*, 1981; Villemant *et al.*, 1988; Di Girolamo *et al.*, 1984; Beccaluva *et al.*, 1990; Ghiara *et al.*, 1989-1990; Civetta *et al.*, 1991a, 1997; D'Antonio *et al.*, 1999b; Pappalardo *et al.*, 1999, 2002b; De Astis *et al.*, 2004; Bohrson *et al.*, 2006; Fowler *et al.*, 2007). Chemical zoning of Phlegrean magmatic reservoirs seems to be another common process, as it is evident from the recognition of a mirrored chemical zoning of the erupted products (e.g., Di Girolamo, 1970; Armienti et a., 1983; Melluso *et al.*, 1995; Civetta *et al.*, 1997; de Vita *et al.*, 1999; Pappalardo *et al.*, 2002a; Fedele, 2006; Fedele *et al.*, 2006, 2008, in press).

Finally, restricted to rocks of Ischia island, some authors (e.g., Vezzoli, 1988; Poli *et al.*, 1989; Civetta *et al.*, 1991c) have shown that the products of the five periods of activity are separated by very evident compositional discontinuities. The first of these basically corresponds to the 55 ka MEGT eruption (i.e., the 3rd phase of activity), possibly testifying for a renewal of the magmatic system of the island. Successively, an alkali increase can be observed, followed, at 28.5 ka (4th phase), by a new alkali decrease. A new alkali increase can be detected at 18 ka, followed by a progressive decrease until 10 ka (5th phase), when most of the basic volcanics of the island (predominantly latites and shoshonites) were emplaced.

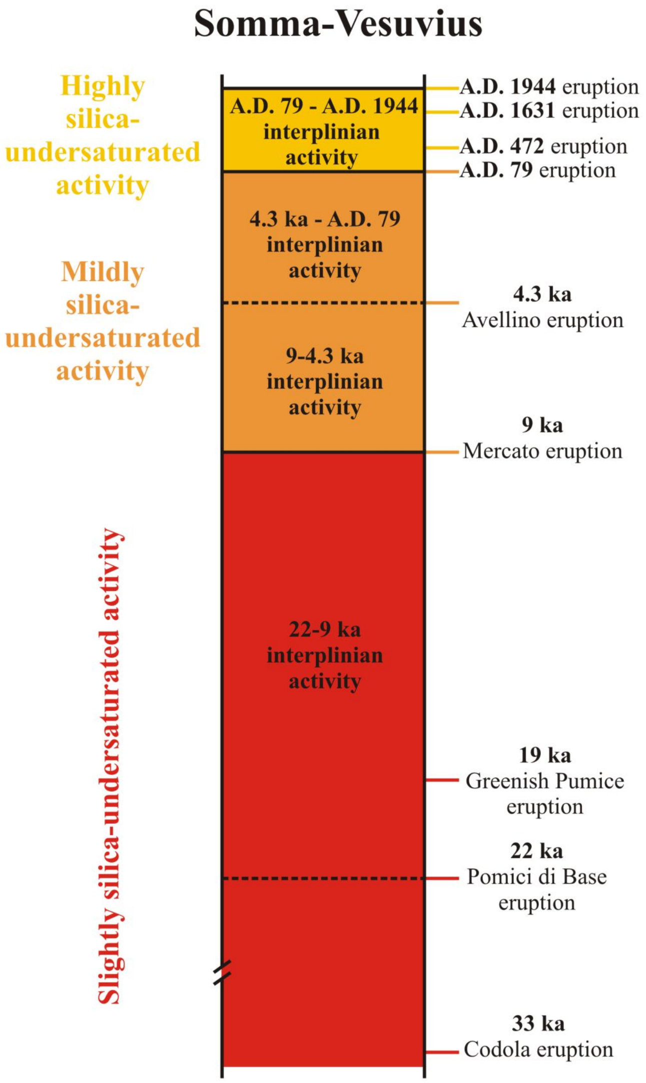
The Somma-Vesuvius

The Somma-Vesuvius (Fig. 1) is a central volcanic complex, sited not far from the south-eastern part of the city of Naples within the Piana Campana semi-graben, at the intersection of conjugate NW-SE and NE-SW fractures (e.g., Principe *et al.*, 1987; Rolandi *et al.*, 2004a). It is made up of an ancient stratovolcano (Mt. Somma) with a summit caldera, in which the more famous cone of the Vesuvius volcano developed. Andronico *et al.* (1995), Cioni *et al.* (1999) and Rolandi *et al.* (2004a) argued for a multicyclic nature of the Somma summit caldera, formed as a consequence of various caldera-forming events. The primitive Somma stratovolcano vent was probably located about 500 m north of the present crater, at the height of ~1600-1900 m (Cioni *et al.*, 1999) or even higher, up to 2000 m if an original crater width of 0.5 km is considered (Rolandi *et al.*, 2004a). The caldera probably developed as a consequence of a multicyclic process related to repeated plinian eruptions (Andronico *et al.*, 1995; Cioni *et al.*, 1999; Rolandi *et al.*, 2004a). Rolandi *et al.* (2004a) proposed a compound model involving an "explosive coring", followed by a repeated "flank failure" caused by phreatomagmatic activity during Avellino and Pompei plinian eruptions. The Vesuvius cone grew up within Mt. Somma caldera after the A.D. 79 eruption (Cioni *et al.*, 1999), mainly due to the interplinian activity occurred between 472 and 1139 and between 1631 and 1944 (Rolandi *et al.*, 1998, 2004a).

The eruptions which characterized the volcanological evolution of the Somma-Vesuvius can be basically ascribed to three different types (Santacroce, 1983, 1987; Civetta *et al.*, 1991b): 1) small volume eruptions (i.e., strombolian and effusive), with the emission of about 0.01 km^3 of magma; 2) medium volume eruptions (subplinian; ~0.1 km^3); 3) big volume eruptions (plinian; >1 km^3). Plinian and subplinian eruptions generally follow a precise eruptive sequence (Civetta *et al.*, 1991b). This seems particularly true for plinian eruptions (mainly because they are much better characterized with respect to subplinian ones), which generally start with the emission of fallout pumice, scoria and ash deposits (the plinian *s.s.* phase) related to the development of a substained column. This magmatic phase can be interrupted by partial column collapses, with associated emplacement of pyroclastic flow deposits, followed by the final collapse of the eruptive column, marked by pyroclastic flow and lahr deposits (e.g., Sheridan *et al.*, 1981; Sigurdsson *et al.*, 1985). The eruption ends with a phreatomagmatic phase (characterized by the emission of “wet” pyroclastic deposits), related to the interaction of the magmas with ground water, due to the emptying of the magmatic reservoirs (Sheridan *et al.*, 1981; Barberi *et al.*, 1989, 1990; Civetta *et al.*, 1991c).

A similar repetitive behaviour can be recognized also in the overall dynamics of Somma-Vesuvius volcanism, which seem to have followed a very simple cyclic mechanism in which periods of quiescence (from hundreds to thousands of years), characterized by obstructed conduit conditions, were interrupted by plinian or subplinan eruptions. Interplinian activity was characterized by open conduit conditions, with small volume semipersistent strombolian-vulcanian activity plus frequent lava effusions and phreatomagmatic eruptions (Civetta and Santacroce, 1992; Rolandi *et al.*, 1998). In addition, Civetta and Santacroce (1992) recognized a positive correlation between erupted volumes, degree of magma differentiation and length of repose periods. The same authors also related the obstruction of the conduit to the formation of large magma chambers, whose depth controlled the styles of eruptions. Reservoir structures developed within the Mesozoic carbonatic basement are associated with very long periods of quiescence (i.e., several centuries), followed by powerful plinian events. Conversely, magma chambers formed above the basement are related to shorter periods of repose (i.e., few centuries) and less voluminous subplinian eruptions. Open conduit activity is probably related to smaller (<0.5 km^3) and shallower (1-2 km depth) reservoirs, constantly refilled by new magma batches (Civetta and Santacroce, 1992; Marianelli *et al.*, 1995).

Figure 9. Geochronology of Somma-Vesuvius eruptions



Chronological sketch summarizing the post-39 ka volcanism of the Somma-Vesuvius complex (from Santacroce *et al.*, 2008), whith different colours indicating different magma compositions. Thick marks refer to significative eruptions. See text for a more detailed treatment.

Very little is known about the ancient Mt. Somma activity. The few available data are mainly restricted to samples recovered in the “Trecase 1” geothermal well, which indicate that Somma-Vesuvius volcanism probably started around 300-400 ka (Bernasconi *et al.*, 1981; Principe *et al.*, 1987; Brocchini *et al.*, 2001) with the emission of tephritic-phonolitic and shoshonitic lavas. This very early phase of activity was probably followed by a long period of quiescence, which ended only after the CI eruption (i.e., ~39 ka), whose deposits represent a widespread marker horizon in the Somma-Vesuvius area. Most of the Mt. Somma products known, represented by the lava flows, spatter and scoria deposits presently observable along the inner walls of the caldera (Santacroce and Sbrana, 2003; Santacroce *et al.*, 2008) and by pyroclastic deposits recovered in the Camaldoli della Torre borehole (Di Renzo *et al.*, 2007), were emplaced after this event.

Several models have been so far proposed for the post-CI volcanological evolution of the Somma-Vesuvius (e.g., Johnston-Lavis, 1884; Rittmann and Ippolito, 1962; Lirer *et al.*, 1973; Delibrias *et al.*, 1979; Arnò *et al.*, 1987; Civetta *et al.*, 1991b; Civetta and Santacroce, 1992; Ayuso *et al.*, 1998; Somma *et al.*, 2001; Piochi *et al.*, 2006; Santacroce *et al.*, 2008). These schematizations differ from each other in many aspects, from the number of the recognized phases of activity, to the dating of the various eruptions, to the classification of each explosive event (e.g., as a plinian or a subplinian eruption), up to the name of a specific eruption. However, an overall concordance can be envisaged as regards the most important points, and therefore it is here chosen to refer to the most recent of these models, the one of Santacroce *et al.* (2008), reported in Figure 9.

Five major plinian eruptions characterized the Somma-Vesuvius activity (Santacroce *et al.*, 2008): Codola [dated at ~25 B.P. by Alessio *et al.* (1974), calibrated at 33 ka by Giaccio *et al.* (2008)], Pomici di Base (or "*Sarno*", ~22 ka; Capaldi *et al.*, 1985; Andronico *et al.*, 1995), Mercato (or "*Ottaviano*", ~8-8.9 ka; Aulinas *et al.*, 2007; Santacroce *et al.*, 2008), Avellino (~4.3 ka; Santacroce *et al.*, 2008) and the A.D. 79 [or "*Pompeii*"; e.g., Sheridan *et al.* (1981), Sigurdsson *et al.* (1985), Civetta *et al.* (1991b), Cioni *et al.* (1992), Lanphere *et al.* (2007)]. Except for the Codola eruption, for which the very few available data do not allow a thorough characterization, all these events have been widely studied and accurately described in all their volcanological and petrochemical aspects.

The Pomici di Base eruption is the oldest among the plinian caldera-forming events of the Somma-Vesuvius (e.g., Delibrias *et al.*, 1979; Capaldi *et al.*, 1985; Arnò *et al.*, 1987; Andronico *et al.*, 1995; Bertagnini *et al.*, 1998; Landi *et al.*, 1999). The eruption (~4.4 km^3 of erupted volume) progressed basically following the above mentioned sequence, starting with a magmatic stage, which emplaced ash, pumice and scoria fallout deposits, and ending with a phreatomagmatic phase, during which lithic-rich pyroclastic fall deposits and flow deposits accompanied the caldera collapse. Interplinian activity following the Pomici di Base eruption was notably variable, alternating low magnitude eccentric flank eruptions, quiescent phases and subplinian events (e.g., the ~19 ka Greenish Pumice eruption; Delibrias *et al.*, 1979; Ayuso *et al.*, 1998; Santacroce and Sbrana, 2003; Santacroce *et al.*, 2008).

The following plinian event was the Mercato eruption (e.g., Walker, 1977; Delibrias *et al.*, 1979; Rolandi *et al.*, 1993a; Cioni *et al.*, 1999; Aulinas *et al.*, 2007), again characterized by the usual progression from a magmatic fallout stage (the main phase, accounting for some ~90% of the total erupted material, on a total estimated volume of ~2-3 km^3 of pyroclasts) to a phreatomagmatic pyroclastic flow stage. However, the Mercato eruption has shown two features which make it unique among the Somma-Vesuvius plinian eruptions, namely the homogeneous chemical composition of the products (whereas the other plinian eruptions all show a marked compositional zoning) and the poorly developed phreatomagmatic phase.

After the Mercato eruption, the Somma-Vesuvius entered a long quiescent period with no interplinian activity, interrupted only by the Avellino plinian eruption (e.g., Lirer *et al.*, 1973; Arnò *et al.*, 1987; Civetta *et al.*, 1991b; Rolandi *et al.*, 1993b; Cioni *et al.*, 2000). The main particularity of this event (~1-2 km^3 of erupted material), whose eruptive sequence still followed the common scheme of Somma-Vesuvius plinian eruptions, is represented by the sharp colour change of the pyroclastic fall deposits, changing upwards from white to grey. This has been interpreted as a clear evidence of a change in magma composition (e.g., Barberi *et al.*, 1981; Civetta *et al.*, 1991b; Santacroce *et al.*, 2008). Interplinian activity following the Avellino eruption was characterized by a very complex sequence of events which are still a matter of very controversial interpretations (e.g., Rolandi *et al.*, 1998; Somma *et al.*, 2001; Andronico and Cioni, 2002).

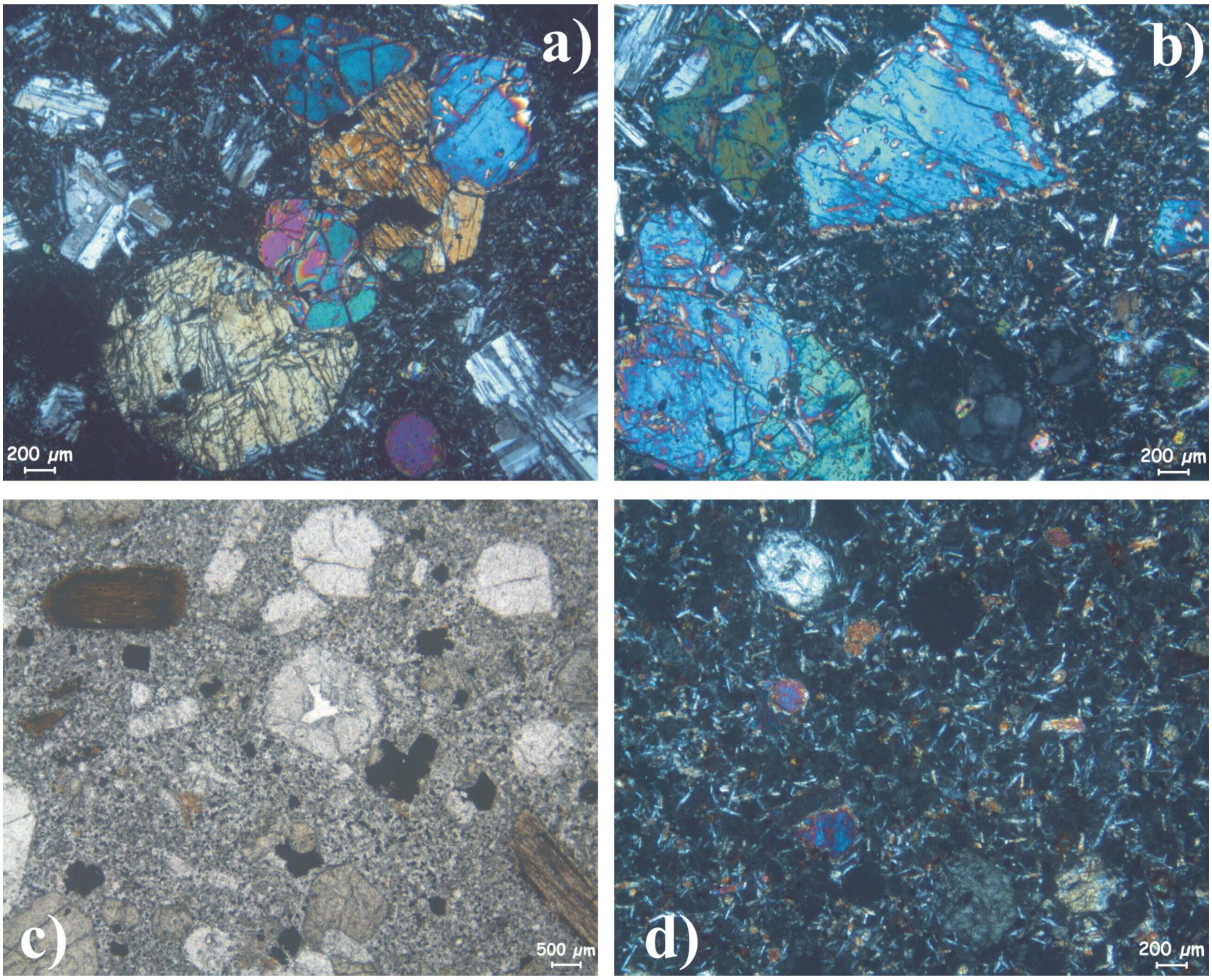
The A.D. 79 eruption is the last and the best known of the Somma-Vesuvius plinian eruptions (e.g., Di Girolamo, 1963; Sheridan *et al.*, 1981, Sigurdsson *et al.* 1982, 1985, Civetta *et al.*, 1991b; Cioni *et al.*, 1992, 1999; Lirer *et al.*, 1995; Luongo *et al.*, 2003a,b; Lanphere *et al.*, 2007). The eruption is once more characterized by a transition between magmatic and phreatomagmatic phases, in which the plinian *s.s.* stage accounts for most of the erupted tephra (~2-4 km^3 in volume). Like the Avellino eruption, a sharp transition can be observed between basal white pumices and apical grey pumices, suggesting magma stratification in the magma chamber.

The most recent period of activity of Somma-Vesuvius, which contributed to the edification of Vesuvius cone, is characterized by a complex alternation of periods of activity (with various explosive character) and quiescent phases [e.g., Santacroce (1987), Andronico *et al.* (1995), Somma *et al.* (2001), Santacroce *et al.* (2008)]. The period immediately after the A.D. 79 eruption was probably characterized by open conduit conditions, which resulted in very low-energy events mainly consisting in ash emissions (Andronico *et al.*, 1995), suddenly interrupted by the A.D. 472 eruption [“*Pollena*”; Delibrias *et al.* (1979); Rosi and Santacroce (1983); Civetta *et al.* (1991b); Rolandi *et al.* (2004b)], the largest Somma-Vesuvius subplinian eruption known. After this event, a period of very variable “medieval” activity begun, alternating lava effusions, moderately explosive eruptions and repose periods (e.g., Santacroce, 1987; Rolandi *et al.*, 1998; Principe *et al.*, 2004), before a new sudden subplinian eruption occurred in 1631 [e.g., Rosi *et al.* (1993), Bertagnini *et al.* (2006)]. After this event, the volcano entered a new open-conduit phase (“modern” activity) characterized by semipersistent mild activity, minor lava effusions and short quiescent periods. Each of this periods of repose was preceded by relatively powerful explosive-effusive polyphased eruptions (e.g., Santacroce, 1987; Arrighi *et al.*, 2001) like the 1944 event, the last eruption of the Somma-Vesuvius complex.

The Somma-Vesuvius products show alkaline potassic affinity (e.g., Santacroce *et al.*, 1987; Peccerillo, 2005 and references therein) and range from slightly to strongly silica-undersaturated. Several authors have related the variability of silica undersaturation degree to the age of the products [e.g., Joron *et al.* (1987), Ayuso *et al.* (1998), Peccerillo (2005)], up to the most recent paper of Santacroce *et al.* (2008), which proposed the distinction of three groups of rocks: 1) slightly silica-undersaturated, older than the Mercato eruption (>8.9 ka); 2) mildly silica-undersaturated, from the Mercato to the Pompeii eruption (i.e., from 8.9 ka to A.D. 79); 3) highly silica-undersaturated, younger than the Pompeii eruption (<A.D. 79). Some exceptions to this schematization do exist, but they can be considered negligible. Regardless of the serial affinity, a correlation between eruptive style and rock compositions seems to exist, with a linear increase of the degree of differentiation moving from the least differentiated lavas through the more evolved pyroclasts from subplinian and plinian eruptions (the latter being characterized by the most evolved compositions; e.g., Joron *et al.*, 1987; Civetta and Santacroce, 1992; Santacroce *et al.*, 2008).

Somma-Vesuvius slightly undersaturated rocks range in composition from K-trachybasalt to trachyte, with moderately to poorly porphyritic textures dominated by plagioclase and clinopyroxene (plus olivine and leucite in the less evolved products, biotite, K-feldspar and amphibole in the intermediate/evolved ones) set into a holocrystalline to hypocrystalline groundmass (Fig. 10a). Rocks of the mildly undersaturated series are phonotephrites, tephriphonolites and phonolites, commonly showing strongly porphyritic textures (with a general decrease of the degree of porphyricity with increasing degree of evolution) with phenocrysts of plagioclase, clinopyroxene and leucite (plus K-feldspar and biotite in the most evolved tephriphonolites and phonolites) set in a groundmass formed by the same phases and glass (Fig. 10b). Rocks from the highly undersaturated series range from leucite tephrite to leucite phonolite and generally show strongly porphyritic textures characterized by phenocrysts of clinopyroxene plus minor leucite and olivine (absent in phonolites) set into a holocrystalline to hypocrystalline groundmass (Joron *et al.*, 1987; Peccerillo, 2005; Fig. 10c-d).

Figure 10. Petrography of Somma-Vesuvius rocks.



Microphotographs of some representative Somma-Vesuvius lavas: a) crossed polars view of a shoshonite from the slightly undersaturated series showing a strongly porphyritic texture with phenocrysts of clinopyroxene, plagioclase and olivine (bottom and center of the picture) with minor leucite microcysts in the groundmass (sporadic rounded extinct individuals); b) crossed polars view of a phonotephrite from the mildly undersaturated series showing a strongly porphyritic texture with phenocrysts of clinopyroxene, leucite and plagioclase; c) plane polarized view of a leucite phonotephrite from the highly understurated series showing a moderately porphyritic texture with phenocrysts of clinopyroxene, leucite, and biotite (right and left side of the picture); d) crossed polars view of a leucite tephriphonolite from the highly undersaturated series showing a moderately porphyritic texture with clinopyroxene and leucite phenocrysts set into a groundmass with diffuse feldspar microcrysts (sparse small laths).

The main chemical features of the most recurrent mineral phases of Somma-Vesuvius volcanics are briefly presented here.

Olivine. In highly undersaturated lavas olivine is present as rare microphenocrysts (Fo_{78-60}) and as small groundmass individuals (Fo_{66-48}), commonly showing extensive zonation. In slightly undersaturated rocks olivine occurs at any degree of evolution, ranging in composition from Fo_{75} (usually in the cores of crystals) to Fo_{40-45} (in the groundmass; Joron *et al.*, 1987), showing a fairly regular Fe and Mn enrichment with increasing degree of differentiation.

Clinopyroxene. Clinopyroxene is an ubiquitous mineral in Somma-Vesuvius products. Three types of clinopyroxene crystals are commonly observed: diopside, salite and Al-Fe-rich diopside (with a general Al and Fe increase with increasing degree of differentiation of the host rock). Obscillatory, normal and sector zonings are very frequent. Clinopyroxene phenocrysts of the slightly undersaturated series have a moderately variable salitic composition ($Wo_{47-44}En_{41-48}Fs_{12-15}$; Fig. 5) and commonly show lower Al_2O_3, higher TiO_2 and lower Wo contents with respect to those from highly undersatured series (Joron *et al.*, 1987). Groundmass individuals are usually Ti-enriched with respect to Al (Joron *et al.*, 1987).

Plagioclase. Somma-Vesuvius plagioclase is generally characterized by strong An contents (even in the more evolved rock compositions), probably due to high temperatures of the melts or high fluid pressure during the crystallization (Joron *et al.*, 1987). Compositional ranges are generally wide (e.g., $An_{41-91}Ab_{8-55}Or_{1-8}$) essentially ranging from bytownite to andesine (Fig. 6).

K-feldspar. Sanidine crystals are confined to sialic pyroclastics and to the groundmass of the most evolved lavas. In latitic lavas sanidine shows more sodic compositions (up to Ab_{38}), whereas in K-richest trachytes and phonolites sanidine crystals are more potassic (~Or_{85}) and show very high Ba contents (up to 1.30 wt.%; Joron *et al.*, 1987; Landi *et al.*, 1999).

Leucite. Leucite is the most common feldspathoid of Somma-Vesuvius products, occurring almost in all volcanics from series of any degree of saturation, being absent only in the products of the older major plinian eruptions (Joron *et al.*, 1987). Leucite crystals typically show significant silica excess with respect to the stoichiometric compositions, particularly evident in rocks from the slightly undersaturated series (Joron *et al.*, 1987).

Mica. Biotite is very common in the most evolved rocks, with a magnesian character and a moderately high TiO_2 content. Fe-richer varieties are confined to the groundmass of sialic products (Joron *et al.*, 1987).

Opaque oxides. Crystals are mainly present as microphenocrysts or in the groundmass of all Somma-Vesuvius volcanics. In the products of recent Vesuvius activity (leucitites) they are present as titaniferous individuals, rich in ulvöspinel component (45-56%; Joron *et al.*, 1987).

On the whole, the Somma-Vesuvius rocks display SiO_2 contents between ~47 and 66 wt.%, CaO <14 wt.%, TiO_2 <1.3 wt.% and MgO up to 7.5 wt.%. Rocks of the three series show very similar differentiation trends which, however, can be easily distinguished from each other on the basis of different contents or different slopes of some key-elements (e.g., TiO_2, Al_2O_3; Na_2O, K_2O; Fig. 7). With increasing differentiation, a general decrease of TiO_2, CaO, Fe_2O_3, MgO and P_2O_5 and an increase of SiO_2, Na_2O and K_2O can be observed. Rb, Nb, Zr, Hf, Th, U, Ta, Pb and Yb are incompatible, Cr, Ni, Sc, and Cu are compatible (Fig. 8). REE patterns show a marked LREE/HREE enrichment. Throughs at HFSE and a Pb spikes are typical features of Somma-Vesuvius normalized diagrams (e.g., Joron *et al.*, 1987; Peccerillo, 2005). The low MgO, Cr, Ni and Co contents indicate that the most “primitive” magmas do not represent primary mantle melts, but that fractional crystallization, with the removal of clinopyroxene, leucite, plagioclase and Ti-magnetite, probably occurred prior to their emplacement (Ayuso *et al.* 1998).

Fractional crystallization is generally thought to be the main evolutionary process, with the different trends of the three series being ascribable to the existence of different parental magmas (e.g., Joron *et al.*, 1987) or to different ratios of clinopyroxene/feldspar fractionation due to variable crystallization pressures (Trigila and De Benedetti, 1993). In addition, petrographic, geochemical, isotopic and experimental evidences suggest that open-system processes such as magma mixing and assimilation of carbonate wall rock also played some role in the evolution of Somma-Vesuvius magmas (e.g., Savelli *et al.*, 1967a,b; Civetta *et al.*, 1991; Civetta and Santacroce, 1992; Cioni *et al.*, 1995; Ayuso *et al.*, 1998; Civetta *et al.*, 2004; Piochi *et al.*, 2006; Iacono Marziano *et al.*, 2008).

The geomaterials in the Neapolitan architecture

The use of building materials of local origin in the Neapolitan area, as well as in many other Italian regions, has been and still is a common tradition, both for the normal building industry and for major structures. The use (or not) of these natural products through the centuries has been conditioned by several factors, including production costs, worker's skill levels and, in particular the choice of the changing architectural styles. Of the available materials, some of them passed these “tests” and were used extensively; however, it should also be noted that in a few cases, poor utilization has had a negative impact on the reputation of certain materials. This is sometimes due to the scarce knowledge from the users of the intrinsic properties of the materials - often a consequence of a lack of importance given to the characterization of the stone and to a lack of appropriate consultation with professional experts. In addition, a deeper knowledge of the mineralogical and petrophysical features of these materials can lead to better interpretation of the weathering processes and, on this basis, to improvements in heritage preservation and restoration projects.

A review of the main materials used in large buildings in Naples urban areas, mainly represented by the volcaniclastic products of the Campi Flegrei and, subordinately, by the Vesuvian and Phlegrean lavas, is presented in the following section with a detailed treatment of their mineralogical and physical-mechanical features as well as a thorough historical excursion on their employment as geomaterials and some remarks on the main weathering processes affecting them.

The Neapolitan Yellow Tuff (NYT)

Figure 11. Quarries in the Neapolitan Yellow Tuff.

Different kinds of quarries in NYT formation. a) and b) underground quarries below Naples town; c) slope quarry in western Campi Flegrei.

The Neapolitan Yellow Tuff (NYT) represents the most used building stone in Neapolitan and regional architecture since Greek times. The deposits of NYT have been exploited for the production of building dimension stones throughout history. For many centuries, this activity was firstly concentrated and developed beneath the city of Naples (Fig. 11a and b), then in open pit quarries placed at the borders of the old town, such as those at Capodimonte, Rione Sanità, Fontanelle, Camaldoli, Petraio and Pizzofalcone. Only in the 16th century, as a consequence of the further urban development of Naples, a growing demand for material, along with the simultaneous forced reduction in urban exploitation, caused a shift to the western sector of Campi Flegrei which suddenly developed a large number of slope or trench quarries (Fig. 11c).

Figure 12. Mineralogy of the Neapolitan Yellow Tuff.

Authigenic minerals in NYT. Chabazite occurs as rombohedral crystals, phillipsite in acicular clusters. Sample from Marano (Naples).

Mineralogical composition of the NYT

The deposits of the NYT are characterized by both pyrogenic and authigenic phases, as a significant portion of these volcaniclastic products of this eruption (>50% in volume) was affected by diffuse zeolitization processes. Among pyrogenic minerals, feldspars prevail, with minor amounts of biotite and pyroxenes. On the other hand, zeolites such as phillipsite, chabazite and analcime (Fig. 12) are the most abundant authigenic phases, along with minor amount of smectite. Quantitative XRD evaluations (Table 1) show phillipsite as the prevailing zeolite of NYT followed by chabazite and, in minor but still significant amount, analcime. The mean content of these phases generally exceeds 50 wt.%, even though it can sometimes reach values of 70-80 wt.%. (de' Gennaro *et al.*, 1982; de' Gennaro *et al.*, 1990).

Table 1. Representative mineralogical analysis of NYT. Sample from Marano (Naples; Colella et al., 2009).

Smectite	**Biotite**	**Feldspars**	**Phillipsite**	**Chabazite**	**Analcime**	**Pyroxene**	**TOT**	**Amorphous**
(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
12	0.5	12	36	19	7	tr.	87	13

The genesis of the authigenic phases of the NYT has always been deeply debated, especially in order to clarify its possible relationships with the lithification of the deposits of member B of Scarpati *et al.* (1993). Many hypotheses, mainly based on mineralogical, volcanological and geochemical data, were formulated to interpret how the process developed. The first author who hypothesized a "lithification due to secondary processes developed in a prevailing glassy matrix and leading to the formation of zeolites" was Scherillo (1955), even though he could not analytically prove it. This hypothesis was successively confirmed by Sersale (1958). In the 1970's many researchers tried to contribute further. Isotopic data suggested that the zeolitization process lasted at least 4000-5000 years (Capaldi *et al.*, 1971). The stratigraphic relationship between the uppermost incoherent pozzolana facies and the underlying lithified tuff, together with the high reactivity of the trachytic glass, suggested a process due to an open hydrologic system (Hay and Sheppard, 1977) or a diagenetic process in continental environment (Sersale, 1978). Successively, the analogy between the composition of zeolites occurring in NYT and that of the volcanic glass (i.e., phillipsite and chabazite) was considered as proof of a genesis within an open hydrologic system (Passaglia and Vezzalini, 1985; Passaglia *et al.*, 1990). The same process was reported by Scherillo and Scherillo (1990) which also considered the particular texture of pozzolana, here defined as “expanded pozzolana”, as a fundamental to enhancing the zeolitization process.

Different conclusions were proposed by other researchers over a period of about 20 years. Some hypothesized a strong relationship between the minerogenetic process and eruptive mechanism leading to the emplacement of the NYT formation (de’ Gennaro *et al.*, 1982, 1987, 1990, 1995b). In particular de’ Gennaro and Langella (1996), based on the the different zeolitization systems proposed by Mumpton (1973) and Gottardi (1989), excluded that any of them could explain the NYT deposits. On the basis of these research efforts, it was thought that the zeolitization of NYT developed immediately after the eruption in a thermally well-insulated system with the presence of a hot aqueous solution of hydromagmatic origin. Vertical and horizontal variations of the degree of lithification are related to water content and temperature changes during the emplacement of the NYT. In particular, the decrease of lithification towards the top and the bottom of the sequence is attributed to a faster cooling of the deposit, thus inhibiting the zeolitization process. The lack of zeolitization in distal areas led the authors to hypothesize a limit to the thickness of the deposit under which the heat dispersion is so fast as to override the zeolitization process. Finally, the lack of authigenic feldspar indicates that the minerogenetic process was interrupted, thus hindering the evolution of the system towards more stable phases (de' Gennaro *et al.*, 2000b).

Petrophysical features of the NYT

Table 2 summarizes the main petrophysical parameters of NYT. Bulk density values, as many of the following reported parameters, range in a quite wide range (10.2-14.1 kN/m^3) as a consequence of the high textural heterogeneity of the tuff (variable amounts and sizes of pumices, lithics, etc.). Apparent density shows a more limited range of values (22.06-22.65 kg/m^3). Bulk and apparent density define this material as a light rock (Primavori, 1997).

Table 2. Main petrophysical features of NYT (Colella et al., 2009).

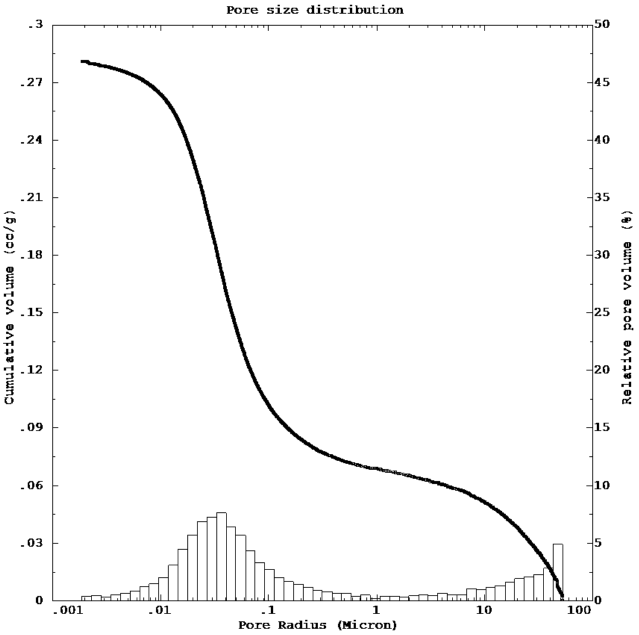
Dry density	**Specific gravity**	**Open porosity**	**Imbibition coefficient**	**Compressive strength (UCS)**	**Ultrasonic velocity**
(kN/m^3)	(kN/m^3)	(%)	(%)	(MPa)	(m/s)
10.20-14.10	22.06-22.65	39.50-63.20	32.51-45.77	0.7-11.9	1602-2267

Total open porosity is definitely high in a wide range of values (39.5-63.2%) thus determining a high attitude of this material at adsorbing water due to the occurrence of a thick net of interconnected pores. Again, this data variability is definitely due to the heterogeneity of the material whereas the high values of porosity should be related to the particular texture of the rock with abundant pumices and lithics set in a ashy matrix deeply transformed in aggregates of phillipsite and chabazite characterized by a microporous structure. The results of Hg-porosimetry are reported in Table 3 and Figure 13. As far as pore distribution is considered, NYT shows a bimodal distribution characterized by a first class, less represented, within the macropores and a second one above the meso-micropore field (0.01-1μm).

Table 3. Parameters determined by Hg-porosimetry on NYT (Colella et al., 2009).

Mean pore diameter (μm)	**Specific surface (m^2/g)**
0.055	18.97

Figure 13. Porosity of the Neapolitan Yellow Tuff.



Pore size distribution obtained by Hg-porosimetry in a NYT sample [after Colella *et al.* (2009), modified].

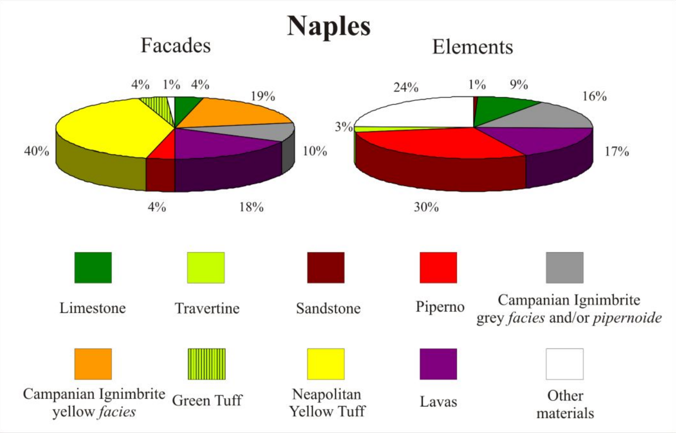
Water absorption by total immersion tests revealed the high attitude of this material in allowing fluid circulation (Table 2) linked to the occurrence of a net of interconnected pores.

Uniaxial compressive strength values range between 4.1 and 6.65 MPa. This low and dispersed values are once again due to the particular heterogeneity of the rock and their textural features, among which porosity plays a relevant role (Evangelista and Pellegrino, 1990). The same features also account for the low and wide ranged ultrasonic velocities (Table 2).

The NYT as building material

The use of NYT as building stone is a thousand-year-old custom. As outlined above, its use is recorded since Greek times, mainly in columns and low-reliefs, but even older examples can be found in some Eneolitic Age tombs (about 4500 years ago). As previously stated, the exploitation was mainly underground, sometimes directly below the construction area. This procedure had some advantages - such as decreasing the cost of material transportation and preserving the surface ground from other anthropic activities. The extended network of underground galleries formed during many centuries beneath the old town was used for several purposes: worship places, rain water reservoirs, cellars or more recently, as air-raid shelter and today, they represent an evocative tourist stop (e.g., see http://www.napolisotterranea.org/. and http://www.lanapolisotterranea.it/). The urban development was strongly determined by the exploitation, thus creating a strong relationship between the urban growth on surface and the creation of a network of caves and tunnels underground (Cardone, 1993).

Figure 14. The building stones of Naples.



Stone material distribution in Naples [after Calcaterra *et al.* (2003a), modified].

The abundance of NYT, along with its good physico-mechanical features and excellent thermal and acoustic coibentation properties (due to the high porosity and the abundance of zeolites in the matrix), resulted in extensive structural use of the yellow tuff - even though in many examples it was used as *facciavista* material (Fig. 14). The most relevant expressions are the Gothic Cathedrals (Basilica di S. Chiara, S. Domenico Maggiore, Cappella Pappacoda, etc.; Fig. 15), the Castel dell'Ovo (Fig. 16) and the Castel Sant'Elmo. Also worth noting are the underground works such as the cripta neapolitana, the grotta di Cocceo, the Volla aqueduct, etc.

Figure 15. Neapolitan stones and monuments.

Belltower of Pappacoda Chapel (1415, restored in 1772) made with NYT, Campanian Ignimbrite and Piperno.

Its use continued in the following centuries in some important buildings such as the Accademia delle Belle Arti (1864), including today as the facades of the municipal swimming pool in Via Consalvo and many other public and residential houses built during the post-earthquake period.

The most successful period in the use of the "nude tuff" in Neapolitan architecture was the Angevin age, as in several gothic style churches such as those of S. Domenico Maggiore (Fig. 17), Santa Chiara (Fig. 18), S. Lorenzo Maggiore, etc. At that time, the Phlegrean stone was being accurately cut, thus providing peculiar architectural elements (arches, rose-windows, capitals, carvings). The choice of NYT as the predominant material was mainly dictated by artistic and architectural preferences, and was not due to needs deriving by economic crises or by autarchic recess. In fact, the Angevin age was one of the most superb periods that Naples, capital of the reign, had ever experienced; thus, it would have been easy to provide even more valuable materials or by using bricks (Cardone, 1990).

Figure 16. The Neapolitan Yellow Tuff as a building stone.

Use of NYT as *facciavista* in the Castel dell'Ovo (XIII-XVI century, Naples).

Figure 17. The Neapolitan Yellow Tuff as a building stone.

Use of the NYT in the S. Domenico Maggiore Church (1283-1324, Naples).

Since the Aragonese age, in contrast, the use of "nude tuff" became rarer and rarer, and walls made in NYT in the new buildings were plastered or coated by slabs of other materials such as Piperno and marble. This was further enhanced by the characteristic of the tuff to adhere to the mortars due to its high surface porosity and roughness. Such adhesion is even stronger with pozzolanic mortars used in Neapolitan architecture, since pozzolana and tuff are the result of different volcanic processes starting from the same original product.

Figure 18. The Neapolitan Yellow Tuff as a building stone.

Use of the NYT in the S. Chiara Chatedral (1310-1340). Reconstructed after a fire in 1943 according to its original baroque style in 50s.

Weathering processes affecting the NYT

The mineralogical composition and the physical properties previously described make the NTY a geomaterial particularly susceptible to the action of the decay agents, as demonstrated by several studies carried out on some wall curtains of important Neapolitan monuments and by laboratory accelerated ageing tests.

Figure 19. Weathering of the Neapolitan Yellow Tuff.

S. Chiara Chatedral, example of esfoliation and disaggregation of the NYT.

In fact, all the *facciavista* surfaces are affected by numerous pathologies such as efflorescences, black crusts, alveolization, scaling, esfoliation which may lead in some cases to severe damage as a consequence of stone disaggregations. The basic agents of all these processes are definitely represented by capillary and surface waters which, by interaction with mortars and the zeolitic constituents of the rock (characterized by a high cation exchange capacity) define the settlement of different pH environments leading to the dissolution of zeolites which represent the cement of the tuff and the consequent tuff disaggregation (Fig. 19).

The Campanian Ignimbrite (CI)

Among local building stones used in the region, the Campanian Ignimbrite (CI) plays a significant role. As discussed in the “Geological outline” section, the CI eruption emplaced a complex and characteristic sequence of deposits, both in proximal and distal facies (e.g., Cappelletti *et al.*, 2003; Fedele *et al.*, 2008), including the Piperno, one of the most important building stones of the Neapolitan architecture. This section focuses only on the tuffaceous deposits of the CI, namely the grey WGI and the yellow LYT facies, reserving the following section to a more detailed treatment on the Piperno.

Figure 20. The Campanian Ignimbrite in a quarry.

Outcrop of the CI in the yellow LYT facies used for the production of dimension stones (Comiziano, Naples).

Because of the abundance of these materials in Campania (Fig. 20 and 21) and their easy workability, they were used extensively in Campanian architecture since Roman times: many facades and/or elements (columns, etc.) of ancient Pompeii are made of tuff, often from the nearby town of Nocera. It has been often used *facciavista* in some relevant monuments such as the Mastio del Castello of Casertavecchia (CE), Castle of Manocalzati (AV), Cathedral of Sessa Aurunca, Basilica of S. Angelo in Formis and the Cathedral of Casertavecchia. The most highly exploited areas were located in the Caserta and in the Sarnese-Nocerino areas even though several quarries were identified over the whole region (Penta, 1935).

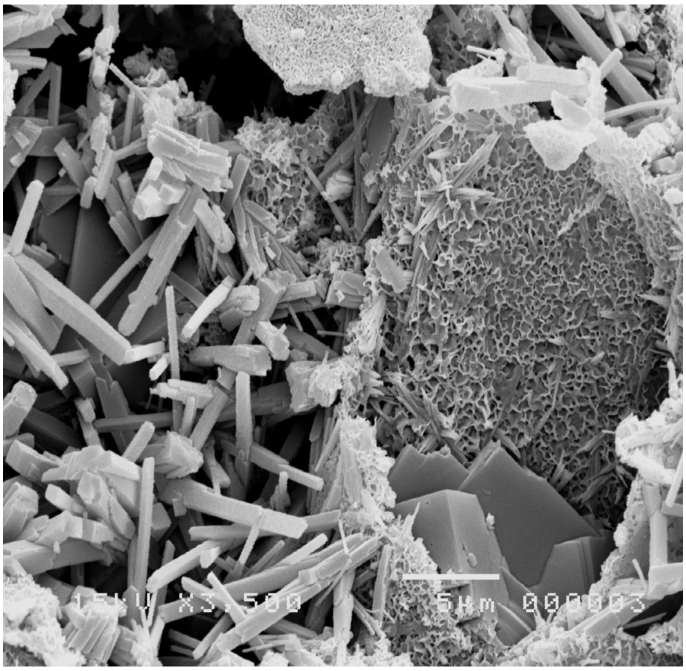
Figure 21. The Campanian Ignimbrite in the field.

Outcrop of CI in the grey WGI facies showing typical columnar jointings (Tufara, Benevento).

Mineralogical composition of the CI

The most relevant WGI facies of the CI, historically referred to as the “Campanian Grey Tuff”, is mainly constituted by K-feldspar and plagioclase, together accounting for ~90% (Table 4). Clinopyroxene, biotite and hematite are definitely subordinate. Meionite was only recorded in some layers of the Sarnese-Nocerino district. The lithification process is mainly related to post-depositional devitrification phenomena leading to the crystallization of authigenic feldspar.

Figure 22. Mineralogy of the Campanian Ignimbrite.



Phillipsite crystals along with smectite and chabazite in CI yellow LYT facies in a sample from Comiziano (Naples).

As regards the overling yellow facies (LYT), the most common mineral phases are represented by phillipsite and chabazite, commonly occurring in similar abundances (Table 4; Fig. 22), sometimes along with minor amounts of analcime and smectite (de’ Gennaro *et al.*, 1987; Cappelletti *et al.*, 2003). The genesis of such authigenic phases is probably related to interactions between infiltrating waters and the glassy matrix in a still hot system. Pyrogenic phases are feldspar (about 20%) and biotite in traces.

Table 4. Representative mineralogical analyses of CI grey (WGI, Piedimonte di Casolla, Caserta; Calcaterra et al,. 2004) and yellow facies (LYT, Comiziano, Naples; Colella et al., 2009). tr. = traces.

	Smectite	**Biotite**	**Feldspars**	**Phillipsite**	**Chabazite**	**Analcime**	**Pyroxene**	**TOT**	**Amorphous**
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Grey facies	-	-	90	-	-	-	-	90	9
Yellow facies	8	1	17	30	25	2	tr.	83	17

Petrophysical features of the CI

Table 5 indicates some technical features of CI. Data for the grey WGI facies refer to a large sampling carried out on the most important outcrops of the formation, whereas those concerning the yellow LYT facies were collected on samples from a quarry in Comiziano (Naples). This explains the much higher variability of each single parameter in the grey facies and the quite homogeneous data in the yellow one.

Table 5. Physical parameters of CI in grey and yellow facies (WGI and LYT, Comiziano, Naples; Papa, 2010).

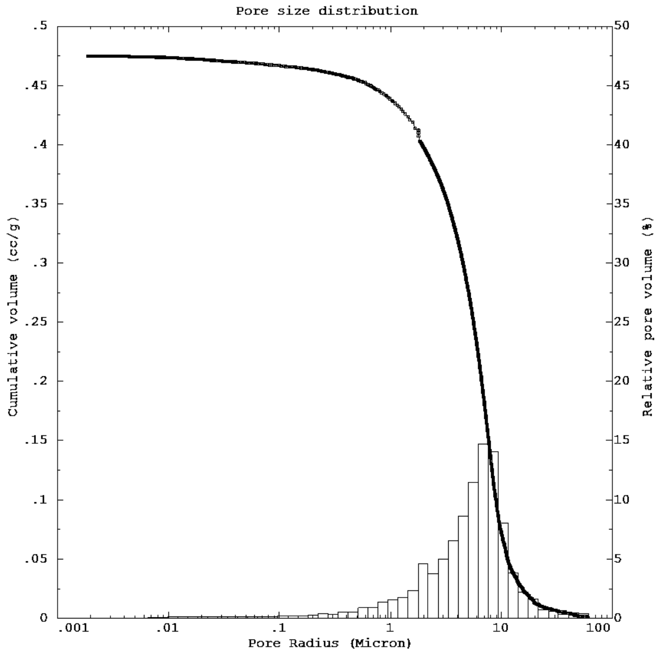
	Dry density	**Specific gravity**	**Open porosity**	**Imbibition coefficient**	**Compressive strength (UCS)**	**Ultrasonic velocity**
	(kN/m^3)	(kN/m^3)	(%)	(%)	(MPa)	(m/s)
Grey facies	10.40-13.40	22.26-25.90	50.40-58.60	42.23-52.28	1.1-7.1	1254-2981
Yellow facies	10.20-12.00	23.10-23.40	49.10-55.40	28.50-30.40	6.6-8	1935-2090

Both facies are characterized by a high porosity associated with a strong tendency to absorb water, and quite low values of uniaxial compressive strengths that, analogous to NYT, are related to the heterogeneity of the rock and to its textural features. On these bases, the two facies are defined as weak, macroporous and light rocks (Primavori, 1997).

Table 6. Parameters determined by Hg-porosimetry on grey (WGI) and yellow (LYT) facies of CI (Papa, 2010).

	Mean pore diameter (µm)	**Specific surface (m^2/g)**
Grey facies	6.84	1.11
Yellow facies	0.79	9.6

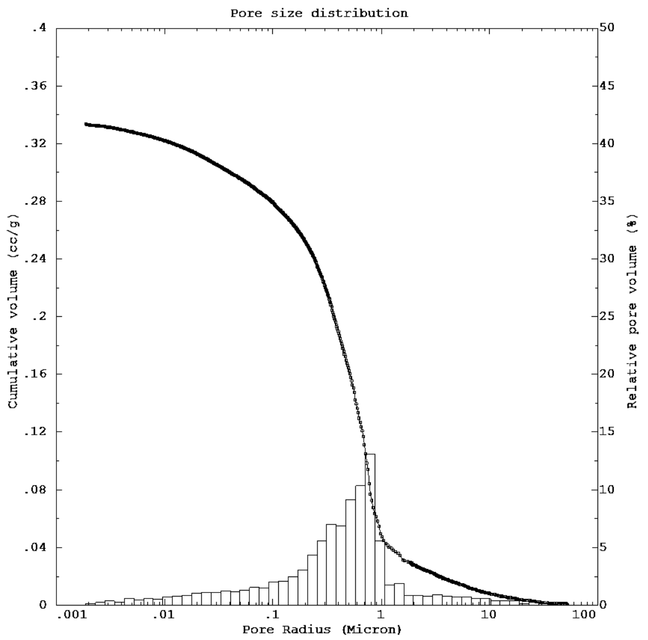
Figure 23. Porosity of the Campanian Ignimbrite.



Pore size distribution for the grey facies (WGI) of CI (from Papa, 2010, modified).

Results of Hg- porosimetric tests are reported in Table 6. Both facies are characterized by an unimodal pore distribution (Fig. 23 and 24) falling in the macropore class. Mean pore diameter is for the grey facies one order of magnitude higher (6.84 µm) than that of the yellow one (0.79 µm). The higher value of specific surface recorded for the yellow facies is definitely linked to the presence of zeolites.

Figure 24. Porosity of the Campanian Ignimbrite.



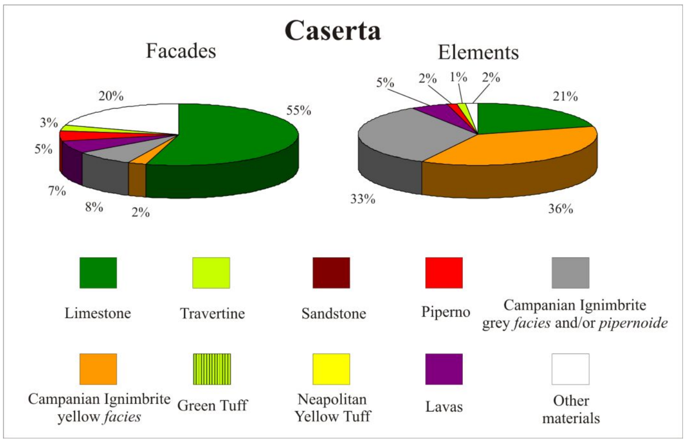
Pore size distribution for the yellow facies (LYT) of CI [after Colella *et al.* (2009), modified].

The CI as building material

The widespread occurrence of this product on the Campanian territory along with its good technical features and easy workability made this volcanoclastite one of the most used building stones in the Campanian architecture (Cardone, 1990; de' Gennaro *et al.*, 1995a).

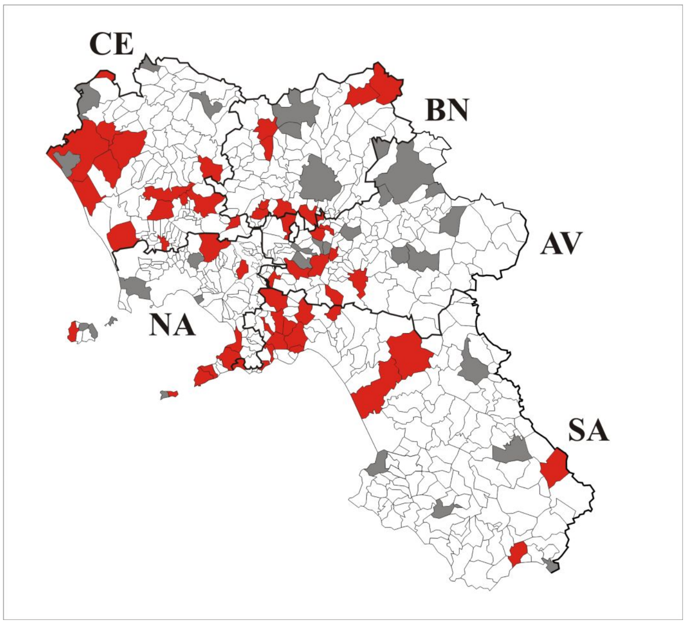
The main sources are located in the Caserta province and in the Sarnese-Nocerino district, even though several quarries have been identified in the region. The yellow LYT facies, while still being requested and appreciated as a building stone due to its technical features and widespread field occurrence, never had a relevance comparable to that of the grey WGI facies in the historical architecture. As far as the Casertavecchia Mastio is considered, recent studies show some minero-petrographical differences thus giving rise to some doubts about the provenance of this tuff (Calcaterra *et al.*, 2004). Few other examples of architectural works are found where this material was used without a plaster coating.

Figure 25. The building stones of the ancient Caserta.



Distribution of stone materials in Casertavecchia [after Calcaterra *et al.* (2003a), modified].

Figure 26. The Campanian Ignimbrite in the Campanian monuments.



Distribution of Campanian municipalities (red coloured) where CI was recorded in some relevant monuments [after Calcaterra *et al.* (2003a), modified].

The grey facies, due to its easy workability and better petrophysical features, has been frequently used in particular architectural elements. Valuable examples of uses of this material as *facciavista* are widespread on the region; however, a particular concentration was recorded in the Caserta province (Fig. 25 and 26). Former examples date back to the 7th century B.C. with the Matres Matutae, votive sculptures symbolizing fertility and abundance, currently located in the Archaeological Museum of Capua; Campanian Ignimbrite, alone or along with other materials was therefore one of the first building materials since Roman times, as testified by the ruins of theatres, bridges, tumbs and the city walls of the old Suessa (today Sessa Aurunca), Pompei, S. Maria Capua Vetere and Treglia (Caiazza, 1986; Villucci, 1980). The popularity of this material, due to its color hues and texture, is admirably expressed in the Cathedrals of Sessa Aurunca, S.Angelo in Formis and Casertavecchia (Fig. 27).

Figure 27. The Campanian Ignimbrite as a building stone.

Belltower of the Cathedral in Casertavecchia made in the grey facies of CI (WGI) and marble.

During the Gothic period (12th - 15th century) the CI was being largely used as load-bearing structure but, at the same time, it started to be used to make decorative elements. Nice examples can be found in the towers of Federico II in Capua, Fieramosca building and Antignano palace in Capua and in the Church of Annunziata in Carinola (Caserta), the latter in gothic-catalan style (Robotti, 1983; D’Angelo, 1958). It cannot be disregarded, in addition, the wonderful decorative effect obtained by combining the grey tuff with other materials (travertine and bricks) in the medieval quadriportico of the Salerno Cathedral (Fig. 28).

Figure 28. The Campanian Ignimbrite as a building stone.

Detail of quadriportico of the Salerno Cathedral in grey facies of CI (WGI) with travertine and bricks.

Finally, the 16th century started the decline in the use of CI used *facciavista*, even though an outstanding example from this period is the Caroline aqueduct (close to Maddaloni) constructed by Vanvitelli (Maiuri, 1950).

Although its use was prevailingly local, the main example of exportation is to Naples where CI had a particular relevance mainly at the end of 19th century replacing the less available Piperno to produce architectural elements and less exposed portions of buildings (Fiengo and Guerriero, 1999; Calcaterra *et al.*, 2000a). Possible areas of provenance of the material used in this period are those mainly located in the Nocerino-Sarnese area and, probably, in Puccianello (Caserta Province).

Weathering processes affecting the CI

The two facies of Campanian Ignimbrite, the welded WGI with prevailing authigenic feldspar and the yellow LYT deeply zeolitized, due to their different composition and texture, generally show different weathering forms. The grey facies is more sensible to the physical action of the decay agents, the yellow one to the chemical action of environmental factors (de' Gennaro *et al.*, 1995a).

Figure 29. Weathering of the Campanian Ignimbrite.

Casertavecchia Castle Mastio, example of disaggregation and alveolization in the yellow facies of CI (LYT).

Figure 30. Weathering of the Campanian Ignimbrite.

Casertavecchia Castle, example of alveolization in the grey facies of CI (WGI).

For both facies the weathering is particularly evident when the stone is contacting different materials; alveolization, patinae, biological activity, scaling and disaggregation are almost always present (Fig. 30). Many facades show a weathering sequence such as: esfoliation → scaling → disaggregation. This final decay phenomenon will expose new fresh surfaces that will be affected by the same weathering. These decay forms are differently developed also as a function of the manufact exposure. Generally, esfoliation, efflorescences and disaggregation are more frequent in buildings south or eastward exposed whereas humidity traces and biological activity occur in those north and westward exposed (de' Gennaro *et al.*, 1995a; Fig. 29 and 30).

The Piperno

The Piperno is surely one of the most well-known and characteristic magmatic building stones in the Neapolitan area. This lithotype is exposed at the northern and southern foot of Camaldoli Hill, at Pianura and Soccavo (Torre Franco and Verdolino).

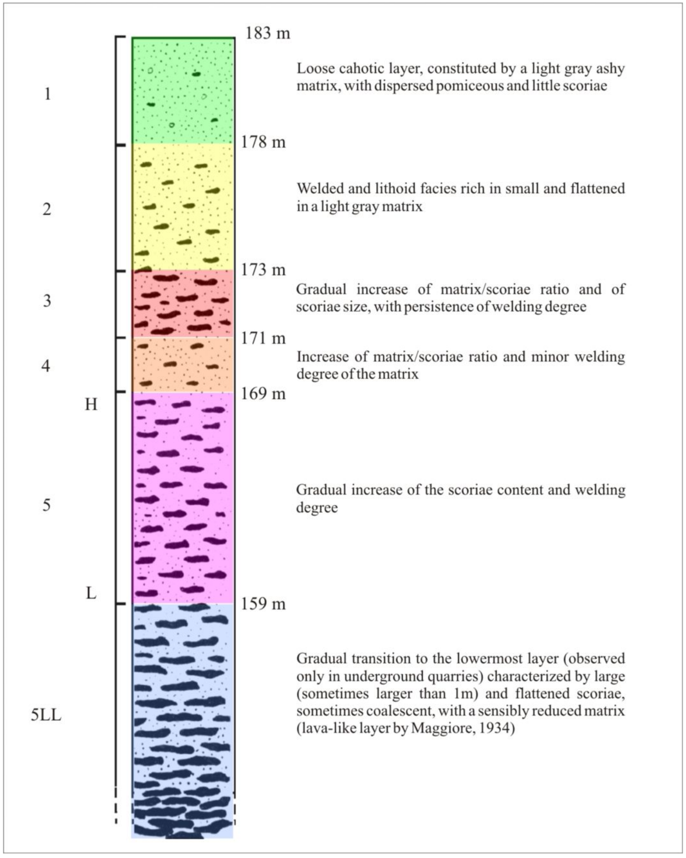
The term "Piperno" probably derives from the Latin piperinus used by Romans to indicate a particular kind of volcanic rock "*lapis piperinus, seu albidus cum punctuis nigris, durus atque fortissimus*" (Isidori Hispaniensis Episcopi, 1911). The only documented quarries are located in the above-cited areas of Campi Flegrei and are formed by tunnels branching under the hill (Carletti, 1787; Cardone, 1990). The formation seems to gently dip northward, but its base is not exposed. However, whenever visible, thickness is about 20 m (Perrotta and Scarpati, 1994; Rosi *et al.*, 1996; Perrotta *et al.*, 2006).

The origin of this deposit has been widely debated. The occurrence of the scoriae, called for the first time *fiammae* by von Buch (1867), led some authors to a very complex interpretation of the depositional mechanism as a lava flow. Since the beginning of the 20th century, many researchers have addressed their attention to this typical deposit. Dell'Erba (1892) and Zambonini (1919) related Piperno to a high temperature "pyroclastic cloud". De Lorenzo (1904) defined it as a trachytic *schlierenlava*. Rittmann (1950) and Gottini (1963) related it to a lava-lake activity. More recently, Fisher and Schmincke (1984) considered the deposit as a welded fallout tuff (agglutinate), whereas Rosi *et al.* (1996) defined Piperno as a pyroclastic flow deposit resulting from a substained activity. In the last years, some authors have differently interpreted Piperno in a wider volcanological context.

Field features are also debated. De Lorenzo (1904) described two layers of Piperno interspersed by breccia layers. Maggiore (1936) accurately described six layers characterized by very different technical properties. These layers have been exploited over different ages. On the other hand, Rosi *et al.* (1996) identified four layers of eutaxitic tuff, interspersed by loose lithic-rich breccias beds. At this time the outcrops are barely accessible and the entrance to the underground quarries are almost hidden.

Among the main Piperno outcropping areas, the section located at Masseria del Monte (Pianura, western side of Camaldoli Hill; Fig. 31) is the most complete in terms of vertical exposure, whereas the other investigated sectors (Piccola Lourdes, Pianura- western side; Verdolino, Soccavo-southern side of Camaldoli Hill) only provide partial information. In addition, data from drilling cores carried out on the slope of the hill for other purposes, gave an overall indication of the possible thickness of the Piperno formation.

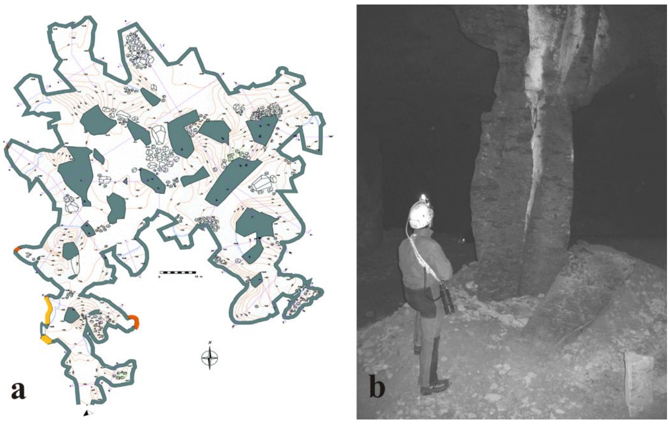
Figure 31. Stratigraphy of the Piperno.



Reconstructed lithostratigraphic sequence of Piperno formation [after Calcaterra *et al.* (2005), modified].

One of the main aims of the studies on Piperno is to rediscover its exploitation sites, located at the foot of the Camaldoli hill, in Naples. In this view, a preliminary investigation showed that, among the main historical underground quarries, the one located in Pianura (Masseria del Monte) was the only accessible for the required studies. The study of the Masseria del Monte site started with a topographical survey (Fig. 32) carried out following the standard techniques adopted in a speleological context. The final report of the survey enabled the editing of a 1:200 scale map and of a relevant number of longitudinal and transversal sections. Finally, the main joints, reporting their dip direction, persistence, the width and possible filling materials, were also surveyed.

Figure 32. Quarry in the Piperno.



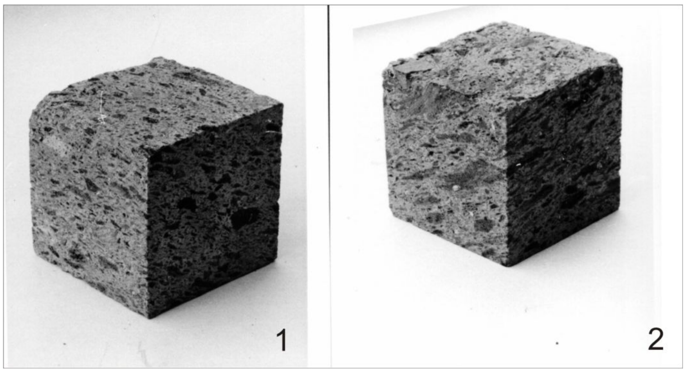
Masseria del Monte, Pianura (NA), map of the cavity (a) and cavity pillar, with evident fissural crack (b).

Mineralogical composition of the Piperno

Piperno is characterized by an eutaxitic texture with black flattened scoriae (*fiammae*) set in a hard and light grey matrix. At a macroscopic scale (Fig. 33) Piperno shows centimeter-to decimeter-sized *fiammae* showing a maximum length of 30-40 cm and an average flattening ratio of 1:10.

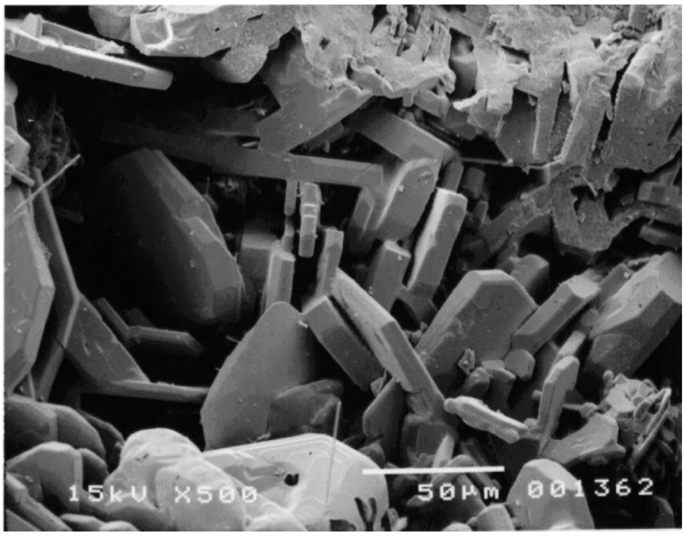
The main phases are sanidine, subordinate plagioclase, clinopyroxene ranging from diopside to salite, biotite, amphibole, magnetite and sodalite. These phases are set in a totally recrystallized matrix, where alkali feldspar represents the neoformed phase (Calcaterra *et al.*, 2000b, c). *Fiammae* are also recrystallized by tiny new crystals of alkali feldspar with the same composition as those of matrix. Table 7 reports the results of a mineralogical quantitative evaluation carried out on representative samples of Piperno from Pianura and Soccavo. For both groups of samples the prevailing phase is sanidine ranging between 89% and 95%. Subordinate amounts of sodalite and magnetite were also recognized. The only Pianura sample shows a residual fraction of unreacted glass (about 5.5%). Only a very limited portion of feldspar can be ascribed to a primary genesis, most of it deriving from devitrification processes (vapour phase crystallization) which involved the glassy fraction occurring both in the matrix and scoriae. These processes led to significant lithological changes. The large glassy scoriae as well as the matrix lost their primary features thus becoming hard and compact as a consequence of welding and/or feldspar crystallization that also reduce the available pore space.

Figure 33. Piperno rock samples.



Specimens of Piperno showing the typical eutaxitic texture. Samples from Pianura (1) and Soccavo (2). Sample size: 71 mm [after Calcaterra *et al.* (2000c), modified].

Figure 34. Mineralogy of the Piperno.



SEM micrograph of feldspar crystals growing on the residual glassy matrix.

Table 7. Mineralogical quantitative evaluation of representative samples of Piperno from Pianura and Soccavo (Calcaterra et al., 2000c). tr. = traces.

	Feldspars	**Sodalite**	**Magnetite**	**Biotite**	**Amphibole**	**Amorphous**
Pianura	95.4	3.5	0.5	-	tr.	0.8
Soccavo	89.3	3.9	1.5	tr.	-	5.4

The products of vapour phase crystallization in Piperno are alkali feldspars with a narrow range in chemical composition ($Or_{53–34}$; Calcaterra *et al.*, 2000b, c). Vapour phase crystallization results from hot gases passing up through the body of the deposit. Some fluids may be of juvenile origin, exsolved from pumice and vitric particles, and some may be from heated groundwater (Calcaterra *et al.*, 2000b, c). These authigenic feldspars are observed in *fiammae* as well as in the matrix and their composition is distinguishable from the few phenocrysts present in the rock (Or_{60-53}). The minerogenetic process seems to be confirmed by many gas-escape pipes present in the upper breccia (e.g. at Verdolino); these vertical channels testify to the wide degassing of the underlying Piperno unit. Electron microscopy observations (SEM) confirmed the above considerations and demonstrated the presence of feldspar crystals, with a typical tabular shape, growing on the glassy matrix (Fig. 34).

Petrophysical features of the Piperno

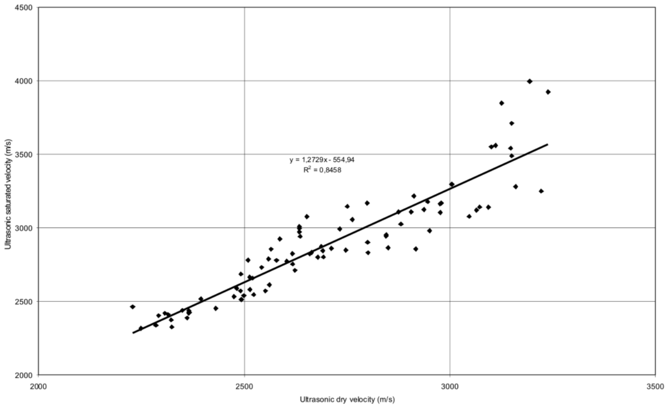
The characterization of the Piperno was formerly attempted bearing in mind the limited extension and the spot size distribution of the formation. Therefore, the entire set of data was handled as a unique population. This analytical approach was also dictated by the chemical and mineralogical homogeneity of the rock.

As far as physical properties are concerned, some representative parameters confirmed that all the analyzed samples can be treated as belonging to a single group. The example reported in Figure 35 shows a good correlation between dry and saturated ultrasonic velocities. However, most of the measured parameters (Table 8) show a marked variability as well; shown, for example, by the open porosity ranging between 12 and 50% (Fig. 36). This wide variability, mainly due to the heterogeneity of the material, can also be ascribed to the oriented texture of the collapsed scoriae (*fiammae*). In fact, some specific non-volumetric parameters (i.e., depending on measurement direction), such as ultrasonic velocities, display higher values after tests performed parallel to the elongation (Fig. 37), both in dry and saturated condition (+11% dry, +13% saturated). The same evidence results from the UCS tests, which, on average, show 23.4 MPa and 29.6 MPa for normal and parallel measurements, respectively.

Table 8. Main petrophysical features of Piperno (Calcaterra et al., 2005).

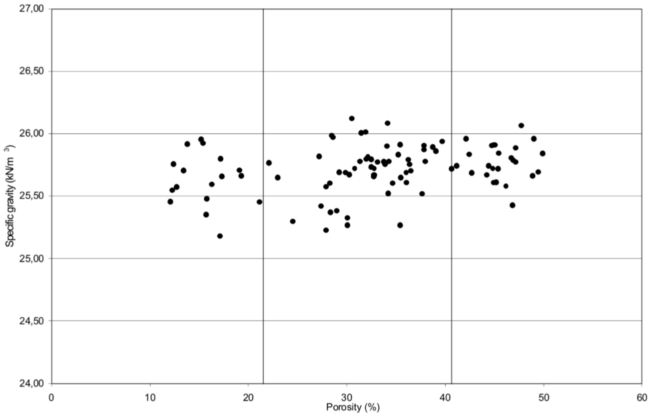
Dry density	**Specific gravity**	**Open porosity**	**Imbibition coefficient**	**Compressive strength (UCS)**	**Ultrasonic velocity**
(kN/m^3)	(kN/m^3)	(%)	(%)	(MPa)	(m/s)
12.95-22.59	25.18-26.12	12.03-49.90	8.66-27.77	4.7-67.5	2229-3239

Figure 35. Technical features of the Piperno.



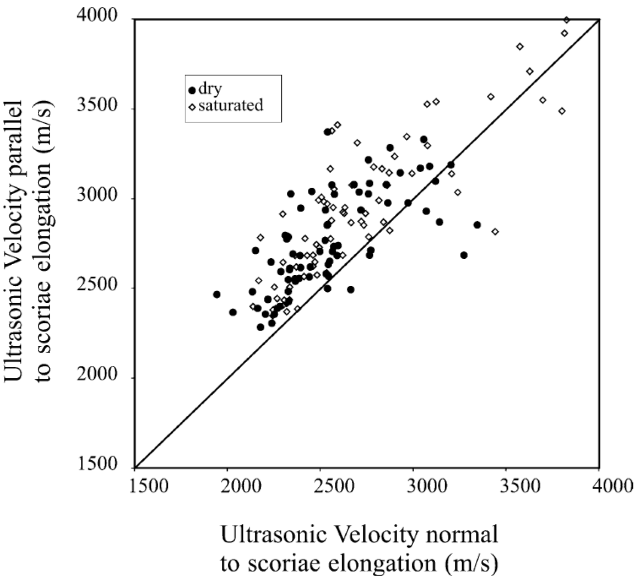
Dry vs. saturated ultrasonic velocity for Piperno [after Calcaterra *et al.* (2005), modified].

Figure 36. Technical features of the Piperno.



Porosity vs. Specific Gravity for Piperno [after Calcaterra *et al.* (2005), modified].

Figure 37. Technical features of the Piperno.

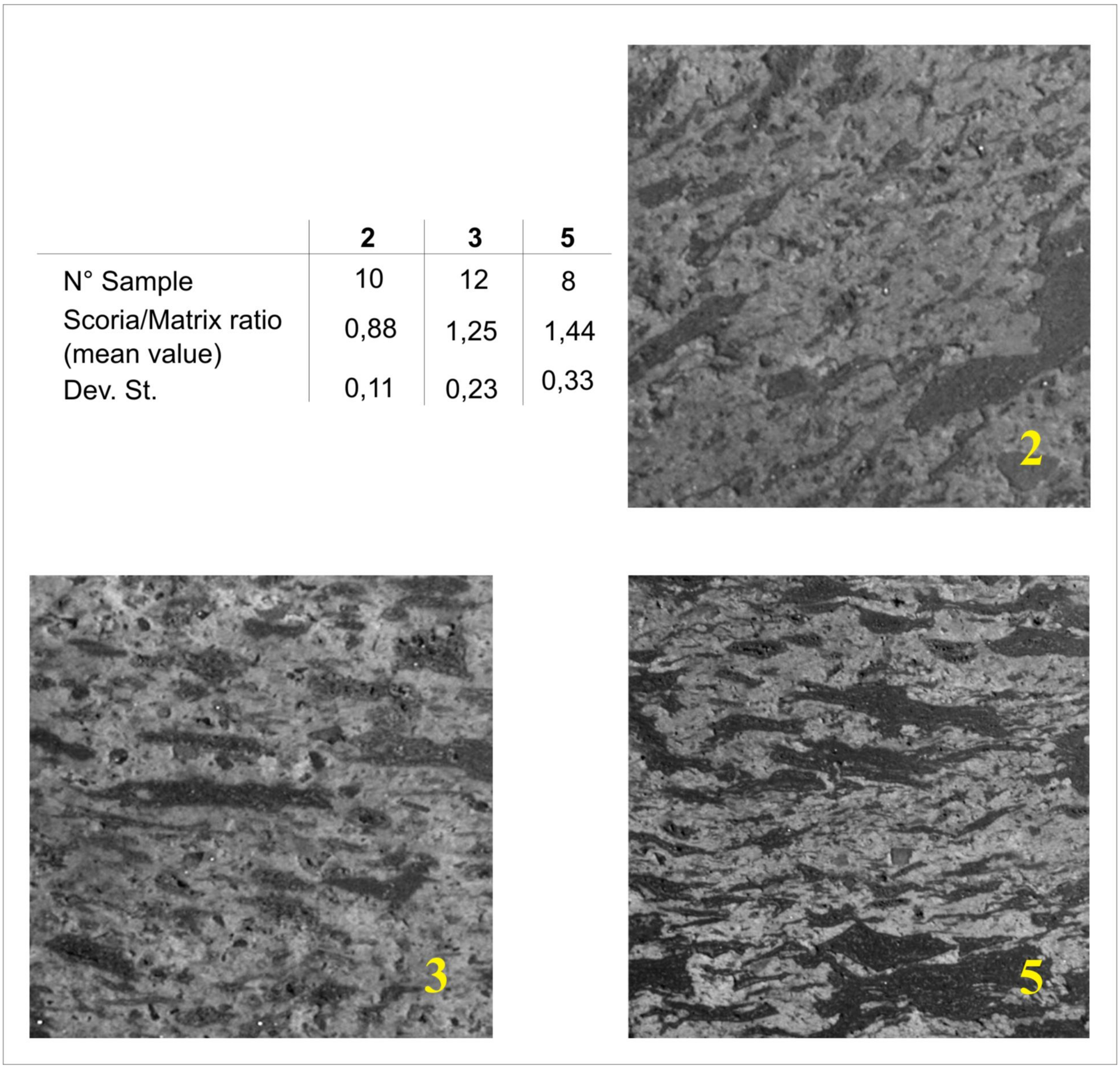


Ultrasonic velocities measured normal and parallel to the elongation, both in dry and saturated condition for Piperno [after Calcaterra *et al.* (2005), modified].

A tentative explanation of this behaviour, that requires further investigation (i.e., by integrating these tests with image analyses), is given by the role played by the morphology of the *fiammae* and their dimension. In fact, it is similarly hypothesized that the direction normal to the scoriae flattening axis “intercepts” a higher amount of denser material (*fiammae*) thus, deeply influencing the measured parameter. The above reported considerations led Calcaterra *et al.* (2004) to revise the petrophysical results taking into account also the lithostratigraphical reconstruction, hence coupling the laboratory data to the aforementioned layers.

In fact, a first confirmation of the relevant role played by the scoriae/matrix ratio is given by an image analysis carried out on samples collected from layers 2, 3/5H and 5L (Fig. 38). Mean values of the scoriae/matrix ratio show a remarkable and progressive increase from layer 2 to layer 5 (maximum difference ranging between 60 and 65%). The wide variability of the textural features is also shown by other experimental relationships such as Uniaxial Compressive Strength (UCS) versus Dry Density (Fig. 39), UCS versus Dry Ultrasonic Velocity (Fig. 40) and Porosity vs. Dry Specific Gravity (Fig. 41). In all graphs three distinct clusters, with a progressive improvement of petrophysical features (2<3/5H<5L) can be identified. Moreover, layers 2 and 3/5H, characterized by UCS values <25 MPa, can be classified as weak rocks whereas layer 5L falls within the field of the hard rocks (Hawkins, 1998).

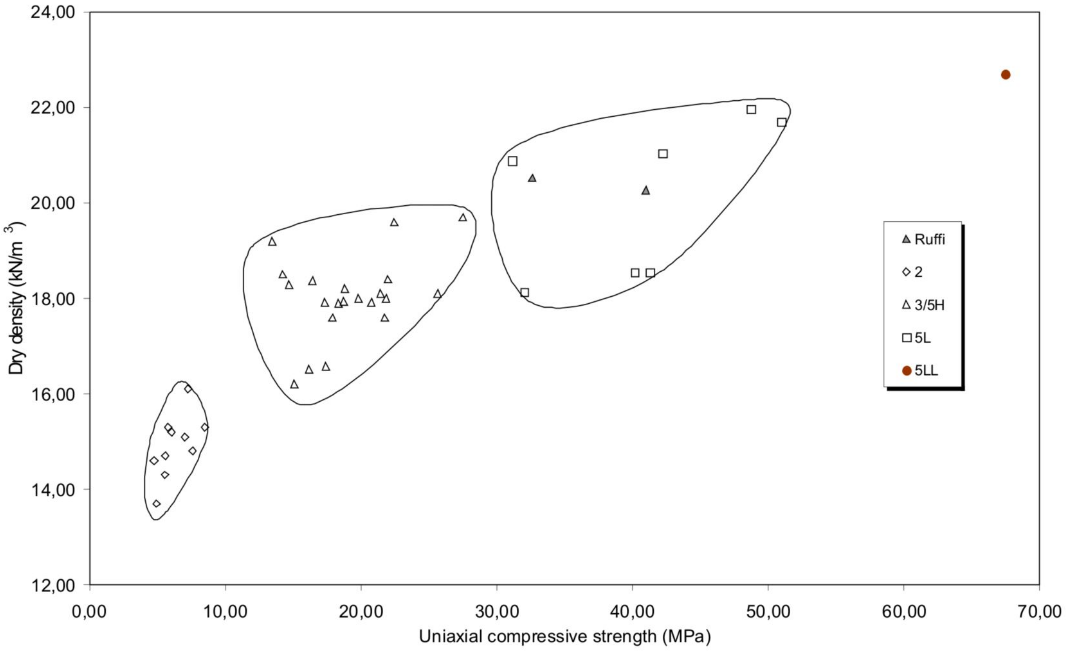
Figure 38. Technical features of the Piperno.



	2	**3**	**5**
N° Sample	10	12	8
Scoria/Matrix ratio (mean value)	0,88	1,25	1,44
Dev. St.	0,11	0,23	0,33

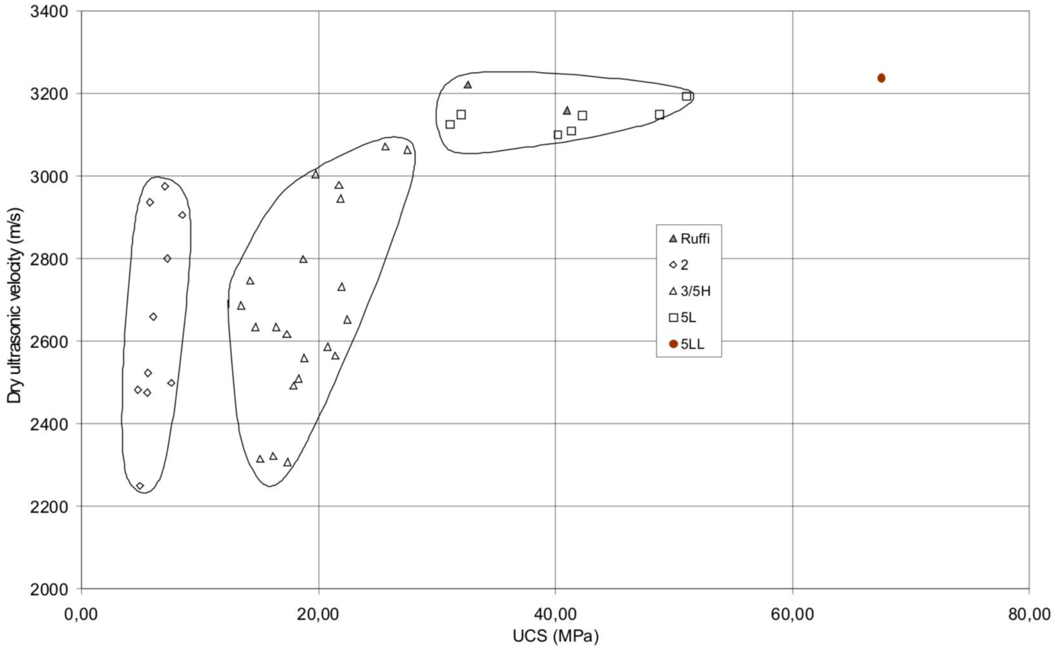
Scoriae/Matrix ratio for the main layers (2, 3 and 5) of Piperno exploited as ornamental stone [after Calcaterra *et al.* (2005), modified].

Figure 39. Technical features of the Piperno.



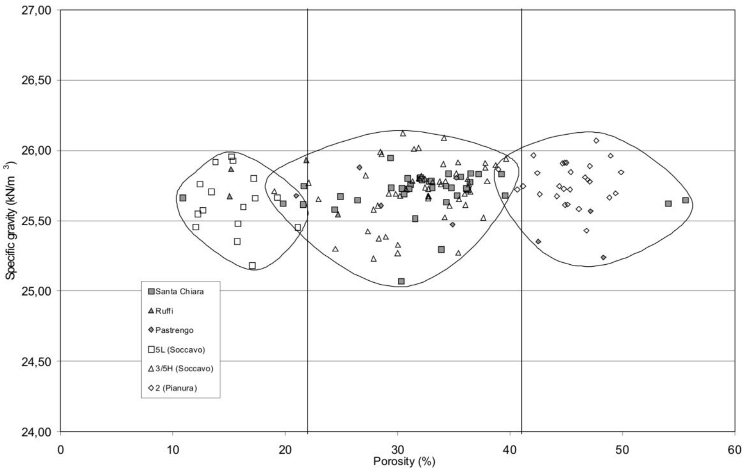
Uniaxial Compressive Strength vs. Dry Density for Piperno samples collected in the field and on monuments [Ruffi = Church of S. Giuseppe dei Ruffi; after Calcaterra *et al.* (2005), modified].

Figure 40. Technical features of the Piperno.



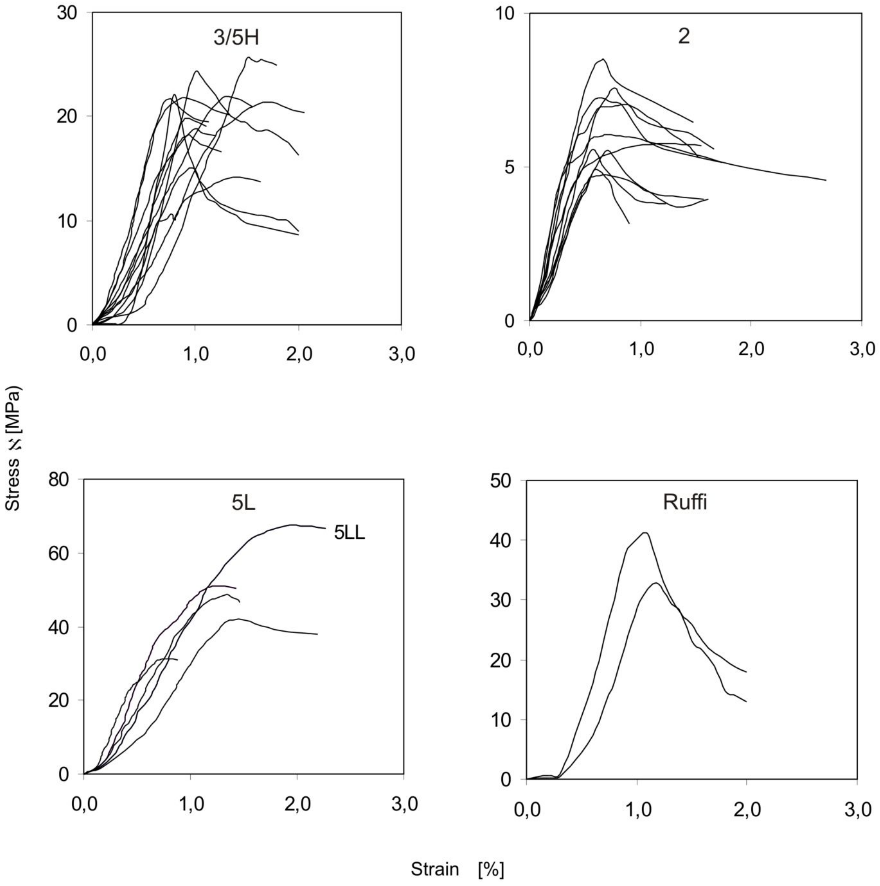
Uniaxial Compressive Strength vs. Dry Ultrasonic Velocity for Piperno samples collected in the field and on monuments [Ruffi = Church of S. Giuseppe dei Ruffi; after Calcaterra *et al.* (2005), modified].

Figure 41. Technical features of the Piperno.



Porosity vs. Dry Specific Gravity for Piperno samples collected in the field and on monuments [Ruffi = Church of S. Giuseppe dei Ruffi; Santa Chiara = Santa Chiara Belltower; S. Anna = Monastery of S. Anna dei Lombardi Complex; after Calcaterra *et al.* (2005), modified].

Figure 42. Technical features of the Piperno.



Stress-strain diagrams for samples collected in the field (layers 2, 3/5H, 5L) and on monuments [Ruffi = Church of S. Giuseppe dei Ruffi; after Calcaterra *et al.* (2005), modified].

The stress/strain curves of Figure 42 also show some differences in terms of elastic behaviour for layers 2, 3/5H and 5L. On the whole, all the varieties of Piperno should be defined as non-elastic rocks (Farmer, 1968), since they display an initial concavity due to closing of excess pore space or microcracks, and a terminal plastic zone approaching a level of failure strain. Adopting the classification proposed by Deere and Miller (1966), based on the modulus ratio (i.e. the ratio between tangent elastic modulus and compressive strength) all the materials would fall in the Low Modulus Ratio field (<200:1), with a very low degree of stiffness, thus indicating a distinct tendency to non-elastic deformation.

The Piperno as building material

Notwithstanding the fact that the most widespread dimension stone in Neapolitan architecture is the NYT, this material is often protected by plaster, so that Piperno ends up as the most diffused stone used *facciavista* (i.e., about 71,000 m^2 out of 130,000 m^2 of surveyed natural building stones; de'Gennaro *et al.*, 2000a). Historical sources (Cardone and Papa, 1993) testify to quarrying in the rural village of Pianura (nowadays an urban district of Naples) since the 13th century. At that time, under the Angevin kings, Piperno, along with the NYT, represented the most used building stone for some of the most outstanding monuments that are still today a marker in the urban setting of Naples. These include Santa Chiara Church, San Domenico Maggiore Church and the San Pietro a Maiella Church. Further proof of the importance that this quarrying gained with time is given by the name of Soccavo (in Latin, sub cava = near the quarry), another village located at the foot of the Camaldoli hill. Under the Aragonese domination (15th century) the demand for Piperno greatly increased, as a consequence of its use in the main buildings of that time: the Gesù Nuovo Church (Fig. 43), the renovation of Maschio Angioino Castle (Fig. 44), the Royal Palace, the Sanseverino Palace, Cuomo Palace (Fig. 45).

The importance of the stone also led to the creation of a specific guild of workers (pipernieri), which increased in importance from the 15th to the 18th century. The exploitation of Piperno continued mainly through the exploitation of underground quarries at Pianura, Soccavo and Verdolino. The environmental conditions were, however, very dangerous and, on 22 October 1739, 11 miners died as a consequence of a vault collapse while working in one of the underground quarries (Cardone and Papa, 1993).

Figure 43. The Piperno as a building stone.

Gesù Nuovo Church. The façade of this building (begun in 1584 and completed in 1601) is of Piperno ashlar.

Figure 44. The Piperno as a building stone.

Castel Nuovo, also known as Maschio Angioino built in 1279. The current appearance was taken between 1443 and 1458.

From the 18th century onwards, Piperno was progressively replaced by less expensive materials, such as lavas of the Phlegrean and Vesuvian districts that are now seen in many buildings of that period in Naples and other Campanian towns. However, the Piperno quarries of Pianura remained active until the first decades of the 20th century. Today, the textural imprinting of Piperno, when used as a dimension stone in modern buildings, is improperly replaced with a similar volcanoclastic rock coming from the Viterbo area (Lazio region), known as "peperino".

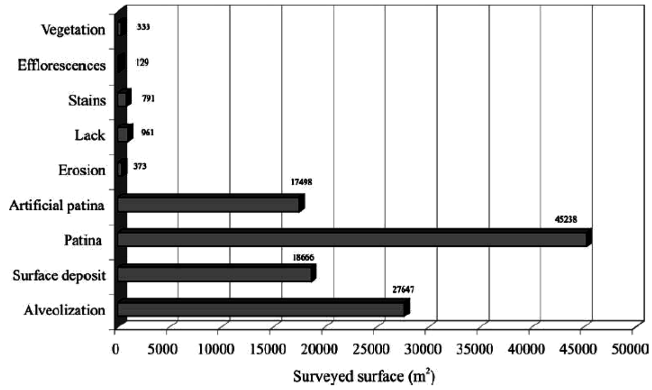
Figure 45. The Piperno as a building stone.

Cuomo Palace, now museo civico Filangieri, 1464-1490.

Weathering processes affecting the Piperno

A first evaluation of the weathering intensity of the Piperno was provided by de' Gennaro *et al.* (2000a), which expressed it as high, moderate and negligible. About 95% of the exposed surfaces was affected by moderate to high weathering grade.

Figure 46. Weathering of the Piperno.

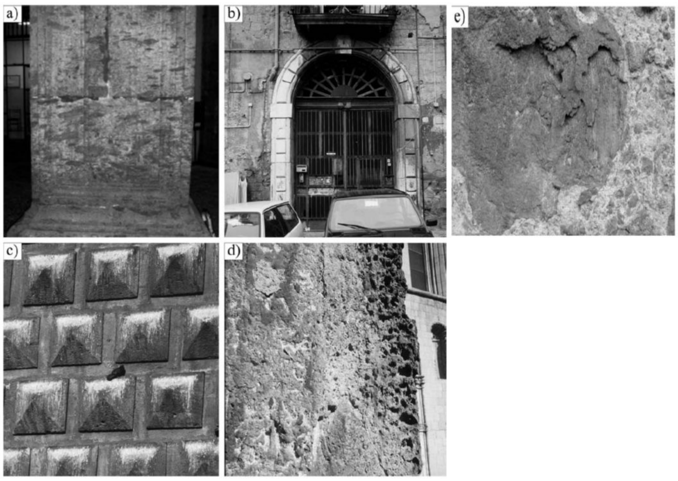


Distribution of different weathering typologies surveyed on Piperno from monuments of ancient centre of Naples [after Calcaterra *et al.* (2005), modified].

The survey carried out in the following research studies (Calcaterra *et al.*, 2004) provided further knowledge on the weathering of Piperno, both in terms of intensity and typology. The weathering typologies were described according to Normal 1/88 (1988). About 87% of the investigated façades and elements is affected by high weathering. Patina, both natural and artificial, is the most diffused weathering typology, followed by alveolization and surface deposits (Fig. 46). Minor typologies are lacks, stains, erosion and vegetation.

Some examples of the most important weathering typologies are reported in Figure 47. Patina (Fig. 47a) produces an almost total annealing of the chromatic contrast between matrix and scoriae, thus giving to the whole surface a uniform dark grey colour. The artificial patina prevails in the lower portions of the buildings, mainly due to vandalism (Fig. 47b). The surface deposits are enhanced in buildings characterized by portions projecting from façades (Fig. 47c). Finally, alveolization (Fig. 47d), favoured by the particular texture and heterogeneity of the rock, and disaggregation affecting monuments exposed to marine aerosol (Fig. 47e), where mechanical effects of salt crystallization are more pronounced, are a clear evidence of the narrow relationships between weathering typologies and microenvironmental conditions.

Figure 47. Weathering of the Piperno.



Main weathering typologies on Piperno surface from monuments. a) patina; b) artificial patina; c) surface deposits; d) alveolization; e) disaggregation [after Calcaterra *et al.* (2005), modified].

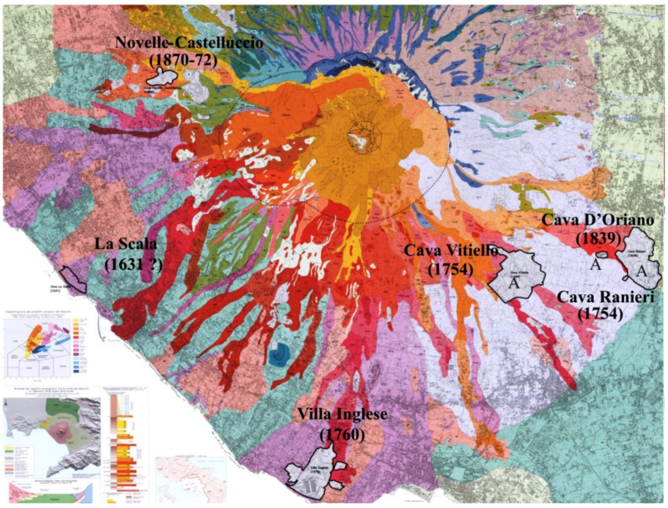
Vesuvian and Phlegrean lavas

Vesuvian lavas used in the architecture of the Neapolitan area belong mainly to the recent historical activity, namely between A.D. 1631 and 1944. Lava flows belonging to this period are located just in the southern sector of the complex and depart from the highest slope of the volcano. In some instances, they reach the sea. Most of the exploitation areas are located in this sector of the Vesuvius.

As far as petrophysical properties of this rock are concerned, literary evidence available is rare and often contradictory. Also, the historical data on the exploitation activity is scarce and incomplete. According to Fiengo (1983), in the middle of the 8th century about ten quarries were still active in an area located around Somma-Vesuviana, Terzigno, S. Giorgio a Cremano, Torre del Greco, Torre Annunziata, Granatello (Portici), and Resina (Ercolano). All these exploitation sites provided a very tough material, particularly suitable for flag-stone roads. The same author, starting from the data of Maggiore (1936), reports that one century later, a few decades before their definitive falling off, the exploitation sites became 74, in most of which lavas emplaced after the 1631 eruption were quarried. Only the paper by Penta and Del Vecchio (1936) reports a complete list of the main quarries (both active and abandoned) occurring on the Vesuvian territory. Most of them, however, were likely placed on old quarry fronts. Among all those reported, only a few can be still recognized and just a couple are active, at the sampling time, as a consequence of the intense urbanization of the area (Fig. 48). The exploitation activity was mainly concentrated in three sectors characterized by important lava outcrops. In the eastern sector, in Terzigno and Boscoreale territory, three sites were identified: the Vitiello quarry, likely representing the old De Medici quarry as reported by Penta and Del Vecchio (1936), which gave the so-called “Mauro lavas” from the flow activity of 1754. The other two sites of this sector, the D’Oriano and Ranieri quarries, are placed on the same lava flows.

The most important exploitation site of the whole Vesuvian district is located in the southern sector of the volcanic apparatus, within the urban limits of Torre del Greco. Known as the “Villa Inglese” quarry, this site was active up to the first half of the ‘70s. Two superimposed lava flows separated by a paleo-soil have been deeply exploited: the upper horizon was attributed by Penta and Del Vecchio (1936) to the A.D. 1760 eruption, whereas the lower one was ascribed alternatively to a presumed effusive event linked to the A.D. 1631 explosive eruption (Penta and Del Vecchio, 1936; Vittozzi and Gasparini, 1964; Rapolla and Vittozzi, 1968) or to older phases of activity (Arnò *et al.*, 1987; Principe *et al.*, 1987). In the same town of Torre del Greco, NW to Villa Inglese quarry another important site named ”La Scala” set out on a lava flow that, according to Penta and Del Vecchio (1936), belongs to the aforementioned presumed effusive event of A.D. 1631.

Figure 48. Vesuvian lava quarries.

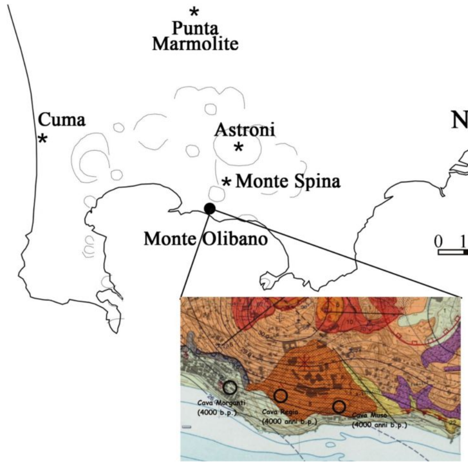


Location of the Vesuvius lava exploitation sites; in brackets the activity age [Somma-Vesuvius Geological Map 1:15,000, from Santacroce *et al.* (2003)]. A = active quarry (in 2002).

In the north-western sector of the Vesuvian area (Ercolano and Somma-Vesuviana) four inactive quarries are present. They can be considered as historical sites quarrying two superimposed lava flows both associated with the 6th cycle of Vesuvius activity (Arnò *et al.*, 1987). Among these sites, only the so-called “Novelle-Castelluccio” quarry (Penta, 1935) still shows a clearly evident front wall.

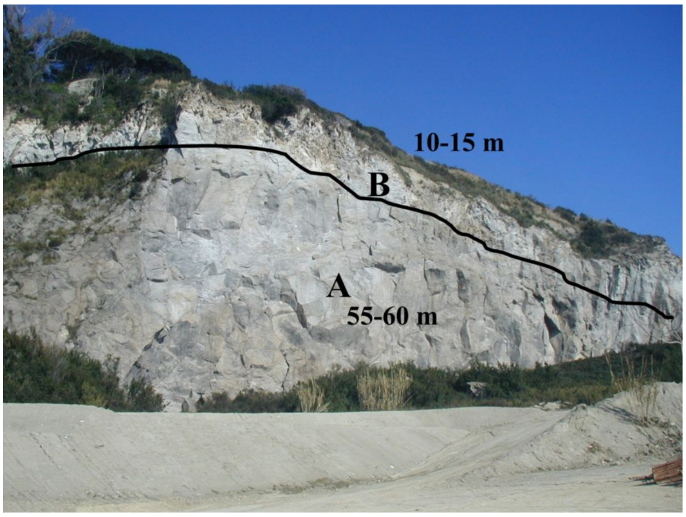
As remarked in the “Geological outline” section, Phlegrean lavas are very rare and limited to small-scale manifestations. They are basically restricted to the young eruptions of Astroni (Di Vito *et al.*, 1999a; Isaia *et al.*, 2004), Monte Spina (de Vita *et al.*, 1999) and Monte Olibano (Di Girolamo *et al.*, 1984; Rosi and Sbrana, 1987; Isaia *et al.*, 2009), and to the pre-CI domes of Cuma, Punta Marmolite and S. Martino (Di Girolamo *et al.*, 1984; Rosi and Sbrana, 1987; Pappalardo *et al.*, 1999; Fedele *et al.*, in press; Fig. 49), in both cases of mainly trachytic composition. Monte Olibano lava flow, definitely representing the most important deposit, was the object of a significant exploitation activity, made even easier via sea transportation facilities (Cardone and Papa 1993). Within this deposit, three different types of lava were identified by Sinno (1955): a basal one, apparently homogeneous, ash grey in colour, where feldspar phenocrysts are hardly distinguishable due to the colour of the matrix; a "powdery" intermediate one, with clearly visible feldspar phenocrysts; an upper one with feldspar phenocrysts evident in a dark grey matrix. As far as petrophysical features are concerned, Maggiore (1936) distinguishes two different typologies of Phlegrean trachytes: a "compact" and a "porous" one. These two different types can even occur within the same flow unit, gradually passing from one variety to another from the bottom to the top of the formation.

Figure 49. Phlegrean lava quarries.



Location of extraction sites of the Phlegraean lavas [Monte Olibano; extract from Geological Map 1:15,000 from Rosi and Sbrana (1987)].

Figure 50. Phlegrean lava quarries.



Front wall of Cava Regia (Monte Olibano, Pozzuoli).

The main exploitation areas of the so-called "Phlegrean trachyte" are represented by some well-preserved old quarries sited close to the west side of the town of Pozzuoli: "Cava Regia", "Cava Muso" and "Cava Morganti", on the Monte Olibano lava dome. Cava Regia is undoubtedly the most important both in terms of thickness and in the amount of exploited material. This is also the only accessible quarry, as the others are located in a military area protecting the Aeronautic Academy. The front wall of the Cava Regia quarry (Fig. 50) is about 70 m high and two different layers can be identified from the bottom to the top: a) an ash grey compact "trachyte" with lighter area (thickness = 55-60 m); b) a light grey less compact and powdery trachyte, deeply fumarolized (thickness = 10-15 m).

Mineralogical composition of the Vesuvian and Phlegrean lavas

All the Vesuvian samples have a porphyritic texture, with clinopyroxene representing the only phenocryst, sometimes along with leucite. Microphenocrysts are represented by leucite, clinopyroxene and biotite. The results of optical microscopy have been confirmed by the XRD analyses, with the identification of the the following minerals: clinopyroxene (42.0-26.6%), Na-plagioclase (33.9-25.1%), leucite (22.6-17.3%), sodalite (4.3-3.4%), sanidine (5.5-3.7%,), biotite (3.3-1.9%), horneblende (2.6-0.2%) and magnetite (0.8-0.1%).

Phlegrean lavas, on the other hand, show a porphyritic texture with phenocrysts of sanidine and, subordinately, clinopyroxene. Microphenocrysts are mostly magnetite and strongly zoned Na-plagioclase. Groundmass is mainly constituted by feldspar, diopsidic pyroxene, brown biotite, magnetite and very-rare plagioclase. XRD quantitative analyses gave the following results in order of abundance: sanidine (80%), Na-plagioclase (6.9-4.5%), diopside (5.7-5.4%), and biotite, magnetite and horneblende in very low amount (1%).

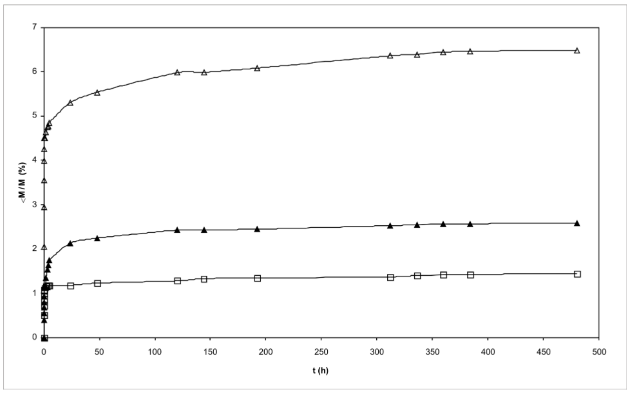
Petrophysical features of the Vesuvian and Phlegrean lavas

Table 9 shows the main physico-mechanical parameters of Vesuvian and Phlegrean lavas. In the former, the low values of open porosity clearly determined a reduced difference between bulk and apparent density, with consequent low values of total water absorption (Fig. 51) and capillary absorption coefficients (Fig. 52). A substantial homogeneity was recorded for the water absorption curves after total immersion in samples from different outcrops. The same remarks apply to capillary water absorption curves which also show an overall homogeneity with only one exception (sample VI) characterized by a higher value, along with the highest total apparent porosity value. A unimodal mesocurtic pore size distribution was also observed with highest concentration of pores in the 0.3-1.2 µm size range (Fig. 53).

Table 9. Main physical properties of Vesuvian and Phlegrean lavas (Langella et al., 2009).

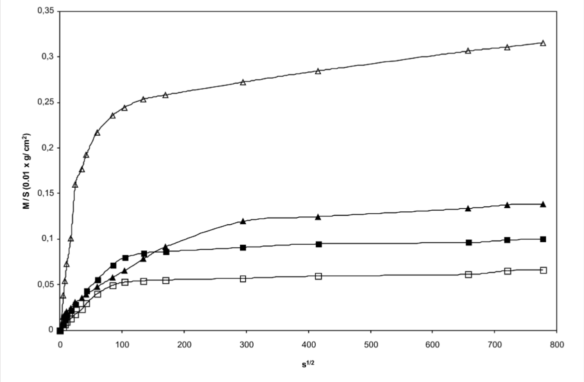
	Dry density	**Specific gravity**	**Open porosity**	**Imbibition coefficient**	**Compressive strength (UCS)**	**Young's elastic modulus**
	(kN/m^3)	(kN/m^3)	(%)	(%)	(Mpa)	(GPa)
Vesuvian lavas	25.70-27.10	28.30-29.00	6.46-9.25	1.41-1.63	165-181	26.92-49.98
Phlegraean lavas	21.30-25.00	26.60-27.20	7.67-21.11	1.43-7.31	38-208	12.58-56.80

Figure 51. Technical features of Vesuvian and Phlegrean lavas.



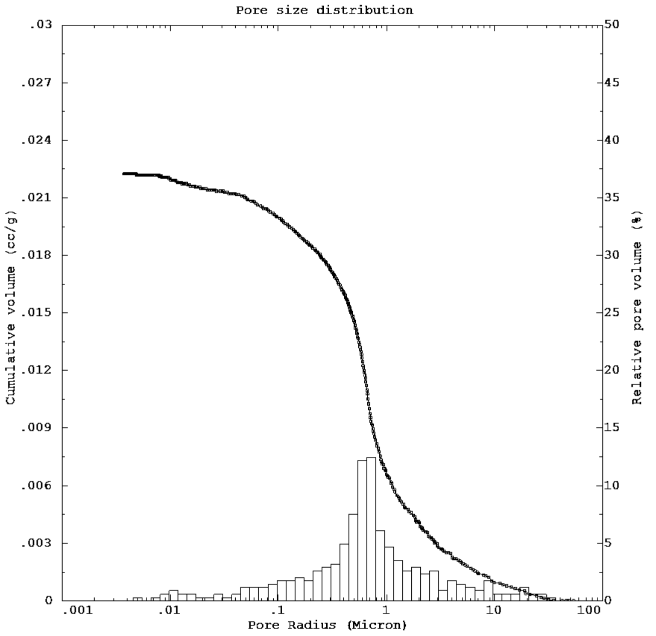
Water absorption curves by total immersion as a function of time [empty squares = Vesuvian lavas; solid triangles = Phlegraean lavas (lower level); empty triangles = Phlegraean lavas (upper level)] [after Langella *et al.* (2009), modified].

Figure 52. Technical features of Vesuvian and Phlegrean lavas.



Capillary water absorption curves as a function of time [squares = Vesuvian lavas, black square = VI sample; solid triangles = Phlegraean lavas from Monte Olibano, lower level; empty triangles = Phlegraean lavas from Monte Olibano, upper level; after Langella *et al.* (2009), modified].

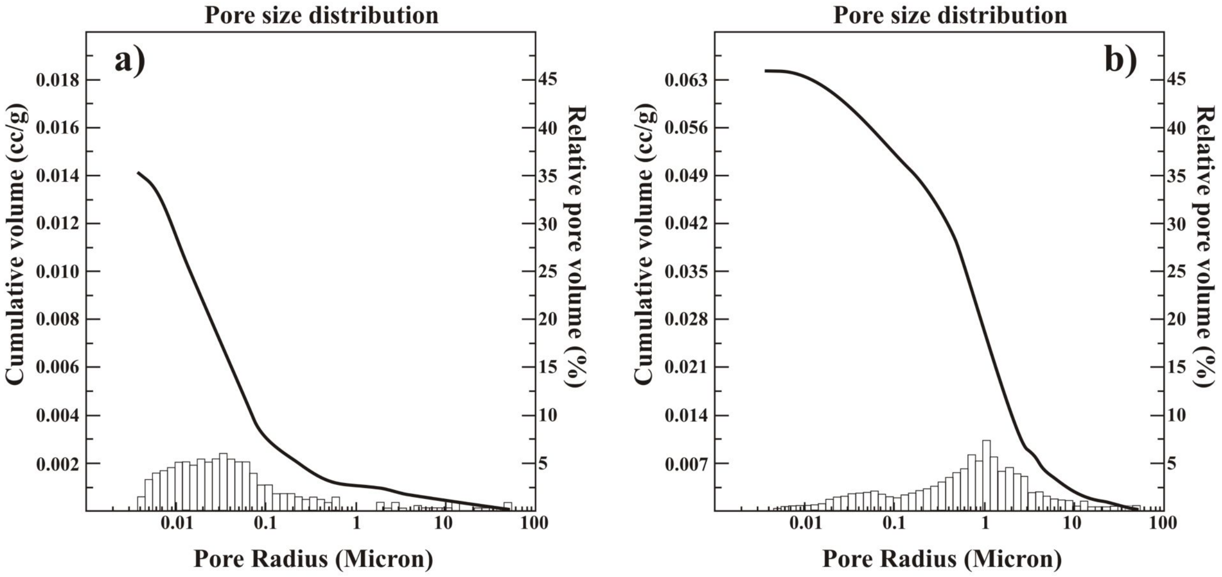
Figure 53. Technical features of Vesuvian lavas.



Pore size distribution in Vesuvian lava sample from Terzigno Tz-1 [after Langella *et al.* (2009), modified].

In the case of the Phlegrean lavas, petrophysical tests were carried out on samples collected from the two layers of the investigated outcrop at Monte Olibano. Lava samples collected from the lower layer (OL1, OL4 and OL5) show a negligible difference between bulk and apparent density and much wider from those belonging to the upper one (OL2 and OL3). This difference is confirmed by the values of total open porosity, close to 10% for the former set of samples and close to 20% for the latter. Pore size distribution also allows us to distinguish two different typologies of material: the first (typical of lava samples OL1, OL4 and OL5) shows low values of open porosity and a unimodal platicurtic pore size distribution; the second one (typical of all the other lava samples) shows a bimodal distribution (Fig. 54). Such variability also occurs in terms of water absorption by total immersion (Fig. 51) and by capillary action (Fig. 52), with the highest values perfectly corresponding to those of porosity.

Figure 54. Technical features of Phlegrean lavas.



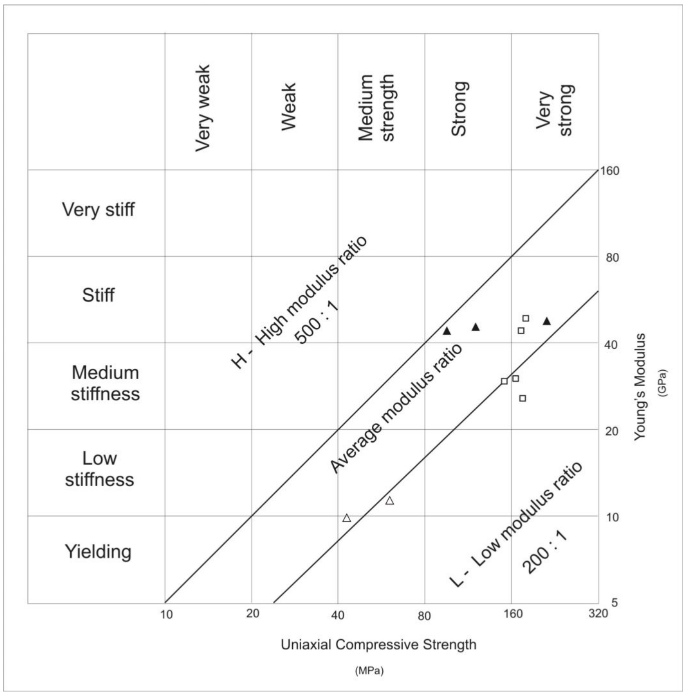
Pore size distribution in Phlegraean lava samples from Monte Olibano OL 1 (a) and OL 2 (b) [after Langella *et al.* (2009), modified].

For uniaxial compressive strength values, a substantial homogeneity of mean values was recorded for Vesuvian samples, ranging between 165 MPa and 181 MPa. These data are very homogeneous and show a very good fit with those of total open porosity, always lower than 10%. Phlegrean lavas, on the contrary, show quite variable mean values of UCS. Two different classes are therefore distinguished: one with values ranging between 138 MPa (OL4 and OL5) and 208 MPa (OL1), and a second one with definitely lower values (38 and 63 MPa, OL3 and

OL2 samples, respectively). It should be said that lava samples characterized by porosity values close to or lower than 10% belong to the first class whereas those with higher porosity values (up to 20%) to the second one.

Young's modulus values confirm the previous considerations even though a higher variability was recorded for Vesuvian lavas (26.92-49.98 GPa). The already reported two-class division for Phlegrean lava is also verified - with a marked homogeneity of the values being noted within each class. Following the classification of Deere and Miller (1966), Vesuvian lavas are defined as strong to very strong and on an average stiff to stiff materials, while Phlegrean ones are considered as strong to very strong and stiff (Fig. 55).

Figure 55. Technical features of Vesuvian and Phlegrean lavas.



Engineering classification of the investigated lavas according to Deere and Miller (1966) [squares = Vesuvian lavas, black square = VI sample; solid triangles = Phlegrean lavas from Monte Olibano, lower level; empty triangles = Phlegraean lavas from Monte Olibano, upper level; after Langella *et al.* (2009), modified].

The Vesuvian and Phlegrean lavas as building materials

Lava has been used as a building stone in the Campanian architecture intermittently, mainly after the second half of the 17th century and, particularly, between the 18th and 19th centuries. Examples of uses of these rocks since Greek–Roman ages are evident nevertheless, principally for paving roads. Notable examples include the roads within the Cuma acropolis (Fig. 56), those present in the archaeological area of the Arco Felice made of Phlegrean trachyte or even those within old Pompei made of Vesuvian lava. Even though the historical use of this stone is definitely subordinate when compared to other more easily workable materials (such as the yellow tuffs (LYT) of the CI) uses of Vesuvian lava in Pompei to perform architectural details such as opus reticolatum (Odeon/Theatre) and columns, or of Phlegrean lava in Pozzuoli (piers of brick arches within the Flavio Amphitheatre) are not lacking (Cardone and Papa, 1993). In the 14th century (1317) a large amount of Phlegrean trachyte was used to pave many roads of Naples town by arrangement of Roberto d'Angiò (Rodolico, 1953).

Figure 56. The Phlegrean lavas as building stones.

Phlegrean lavas used for the paving roads of Cuma acropolis.

Figure 57. The Phlegrean lavas as building stones.

Santa Chiara Church (1310-1328), columns of the arcade.

The period between the end of 13th and 14th centuries signifies an important step in the use of the Phlegrean lava in Neapolitan architecture, as seen in the S. Lorenzo Maggiore (1270-1275; basement and some columns), San Domenico Maggiore (1283-1324; piers of the arches), Santa Chiara (1310-1328; columns of the arcade; Fig. 57), S. Maria Donnaregina (1307-1316; pillars of the choir) and S. Giovanni a Carbonara (1343-1418; big triumph Arch) churches. Some architectural elements of the Maschio Angioino Castle (1281-1284; base of the triumph arch and frames in the Barons' Hall) were also made with lava from Campi Flegrei whose use continued also in the following centuries as confirmed by the 16th century building at Spirito Santo (1539) currently hosting the Banco di Napoli, and the central colonnade of the S. Francesco di Paola Church (1817; Penta, 1935; Cardone and Papa, 1993; Fig. 58). From the end of the 17th century through the end of the 18th century, the increasing use of Piperno (which displayed better technical features), instead of Phlegrean lava is recorded (Cardone and Papa, 1993; Aveta, 1987). Vesuvian lava, also known as "*Pietrarsa*" (i.e., burned stone), only from the 19th century became a fundamental stone in the religious and civil architecture of the town of Naples. This aspect is related to the fact that, only after the 1631 A.D. and subsequent Vesuvius eruptions, a certain amount of material qualitatively and quantitatively suitable for that purpose was available (Penta, 1935; Rodolico, 1953). The main use of lava stone was in slabs for basal coatings [basal facings, such as in S. Giorgio Maggiore Basilica, rebuilt in 1631 and restored in the second half of 19th century (Capuano Castle, twelfth century, 1857); the Federico II University, 1908], or to perform architectural elements such as portals, corner stones, frames, sills, brackets, stairs, etc. (Penta, 1935; Fiengo and Guerriero, 1999). The use of lava for internal coatings or decorative elements was demonstrated by Vanvitelli's work in the Caserta Royal Palace (1752) (Patturelli, 1826). Also worth noting is the combined use of Vesuvian lava (Pietrarsa) and Piperno in the Schilizzi Mausoleum (now the war memorial Votive Altar; Fig. 59) at Posillipo (Penta, 1935) and the huge use in the funeral architecture of the historical part of the Poggioreale Cemetery (Penta, 1935).

Figure 58. The Phlegrean lavas as building stones.

Phlegrean lavas used in the S. Francesco di Paola Church (1817-1846).

Figure 59. The Vesuvian lavas as building stones.

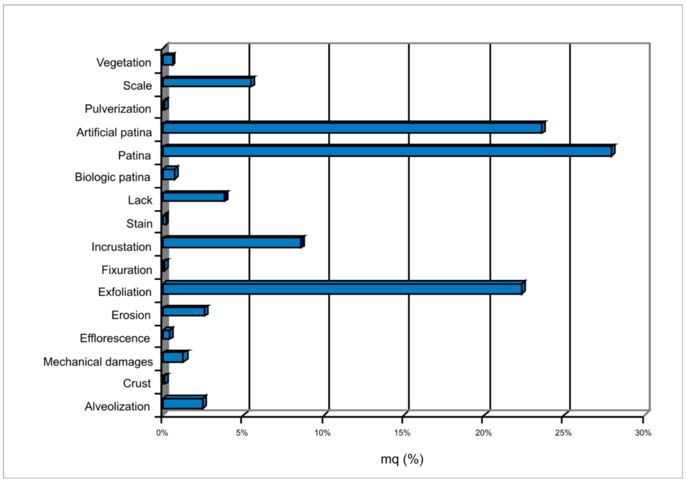
Vesuvian lavas used in the Schilizzi Mausoleum, currently war memorial Votive Altar (1883-1923)

Weathering processes affecting the Vesuvian and Phlegrean lavas

A detailed analysis of the conservation state of the Vesuvian lavas showed that more than 50% of the exposed surfaces are affected by a high-grade decay process, about 20% by a medium-grade and about 23% by a negligible grade (Calcaterra *et al.*, 2000a, b). Previous data have been supplemented with a more complete weathering evaluation, taking particular account of the decay forms and their percentage frequency. Figure 60 reports the weathering forms and the relative per cent frequency for the Vesuvian lavas in the Ancient Centre of Naples.

The most diffused weathering forms are patina and artificial patina (mainly writings and graffiti). More than 20% of the surfaces are affected by exfoliation processes which are manifested by a detachment, often followed by the fall of one or more sub-parallel surface layers (Fig. 61). Incrustations, scaling (Fig. 62), lacks, alveolization and erosion are widespread but with a frequency always lower than 10%. All the remaining weathering forms never exceed 3%. Optical microscopic studies of samples collected from some buildings (Policlinico building on via del Sole) detected a continuous 0.2 mm thick black crust (unresolvable, however, with this technique). Later XRPD investigation identified gypsum as the main mineralogical constituent of these crusts.

Figure 60. Weathering of the Vesuvian lavas.



Weathering typologies affecting the Vesuvian lavas of the Ancient Centre of Naples [after Langella *et al.* (2009), modified].

Phlegrean lavas are definitely subordinate (about 2% of the total) and are mainly concentrated (about 70%, 275 m^2) in the colonnade of the Clarisse Cloister (Santa Chiara Basilica). A comparison with the Vesuvian lavas indicates a slightly worse state of conservation of Phlegrean lava. In fact, ignoring the stone used in the colonnade of the Clarisse Cloister (which is well preserved due to several restorations), 99% of the remaining surfaces are affected by high-grade weathering processes.

Figure 61. Weathering of the Vesuvian lavas.

Example of weathering forms affecting Vesuvian lavas: exfoliation, Via del Sole (Naples).

Figure 62. Weathering of the Vesuvian lavas.

Example of weathering forms affecting Vesuvian lavas: scaling, on basal facing of the Accademia di Belle Arti (Academy of Fine Arts).

Figure 63. Weathering of the Phlegrean lavas.

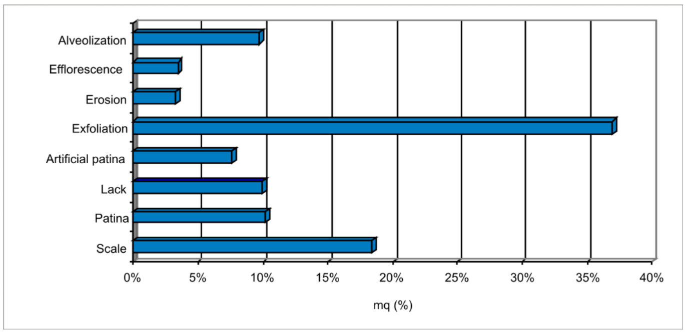
Example of weathering forms affecting the Phlegrean lavas: alveolization, Clarisse cloister, S. Chiara Basilica.

The most diffused weathering typology is undoubtedly the exfoliation, followed by scaling and alveolization (Fig. 63); these lavas are characterized by a more evident occurrence of efflorescences (Fig. 64). The other typologies do not affect more than 10% of the exposed surface (Fig. 65). Again, optical microscope studies (S. Maria La Nova Church) reveal a dark patina about 0.1 mm thick, likely gypsum, and frequent fissures normal to the surface.

Figure 64. Weathering of the Phlegrean lavas.

Example of weathering forms affecting the Phlegrean lavas: efflorescence, S. Chiara Basilica.

Figure 65. Weathering of the Phlegrean lavas.



Weathering typologies affecting the Phlegrean lavas of the Ancient Centre of Naples [after Langella *et al.* (2009), modified].

The Phlegrean "Pozzolana"

A detailed discourse on the uses of geomaterials in the Neapolitan area cannot ignore some aspects concerning the extensive use of the so-called "Pozzolana". This natural product of Campi Flegrei activity, widespread in the Campanian region, was a fundamental component of mortars and plasters since Roman times. The term "pozzolana" refers to a volcanic product, prevailingly glassy with small pumices, lithic fragments and K-feldspar crystals set in an ashy matrix. The glassy component sometimes exceeds 90%. The same term is generally used for all loose products of the Phlegrean volcanism with similar compositional features, even though the most well known and used for its particular features is the pozzolana ascribed to the activity of Fondi di Baia and Bacoli volcanoes.

The prevailing glassy fraction of pozzolana makes it particularly reactive when mixed with lime [$Ca(OH)_2$] and water. The products of this reaction are silicates and calcium aluminates which determine the setting and the hardening of the mortar. Therefore, unlike air-setting limes, these mortars can set underwater. The so-manufactured mortars are definitely better than those made with other inert aggregates. This specific property, as previously stated, was already known in the Roman age; in fact, Marco Pollio Vitruvio in his “De Architectura” distinguishes the volcanic sands from Baia and Cuma suitable for providing hydraulic mortars from other volcanic products that can only be used to produce air-setting mortars. The discovery of hydraulic limes certainly started the production of the commonly defined roman concrete (opus caementicium) - that is, a slurry composed by a mixture of lime, pozzolana, brick fragments and water. This technique enabled Romans to carry out great architectural works such as bridges on Tevere river, many aqueducts and harbours (Ostia, Pozzuoli, Civitavecchia, Anzio). Also, these mortars turned out to be particularly suitable in the Neapolitan area for walls made up of tuff bricks which showed a good adherence to the mortar. On the other hand, this was likely the reason why Vitruvio suggested the use of lime- and pozzolana-based concretes mixed with tuff shards for objects that would not interact with water. This aspect led to a growing demand of pozzolana which was exploited almost everywhere, but mostly in the deposits of Baia and Fondi di Baia, and from there subsequently redirected to the nearby dock. This activity lasted up to the second half of the last century. During this time, several quarries were located in the Phlegrean area, and most of them were active until they were exhausted (Sersale, 1991; Cardone and Papa, 1993; Collepardi, 2008).

Natural hazard factors related to the interplay between geology and anthropical evolution

The geological setting of an area does not just influence the development of its urban settlements by providing geomaterials for the construction of the cities. It also sets the conditions in which the interaction between natural and anthropic dynamics can be disturbed by numerous factors of risk. Apart from the obvious effects of volcanic and seismic activity (by far the most hazardous elements of risk - both continuously monitored by the Italian Civil Protection; see http://www.protezionecivile.it/), two main factors controlling and threatening the environmental and anthropic evolution of the Neapolitan area are represented by landslides and underground cavities.

Landslides

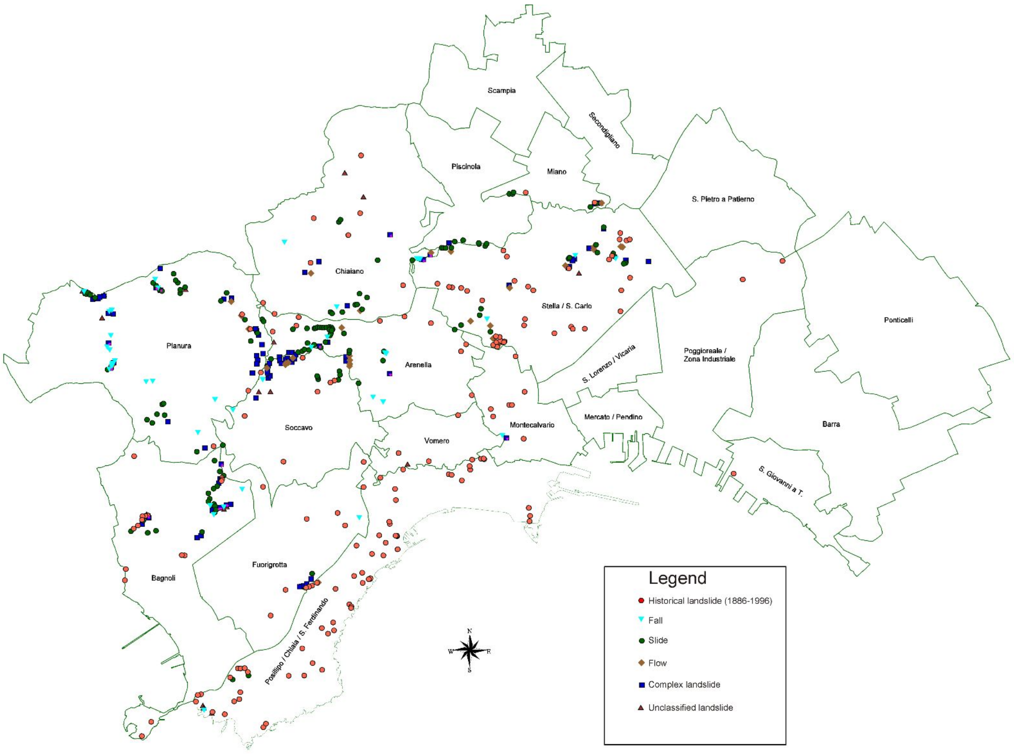
Landslides have had a significant impact on the territorial evolution and safety in the Phlegrean district since historical times. In fact, the earliest evidence which can be related to a slope instability was found in the ancient centre of Naples, in the archaeological site under the San Lorenzo church. Here, 7 m below the present-day ground level, the Imperial age (1st century A.D.) city market is partly buried under a chaotic deposit ascribed to a flood that occurred at the end of 5th century (TCI, 2001), and which probably moved down the slopes of the Caponapoli hill, the northernmost edge of the first Greek-Roman town (5th century B.C.).

In recent years, thorough archival and bibliographic research has allowed reconstruction of the historical landslide activity of the Phlegrean area (Calcaterra *et al.*, 2002d, 2003b), since the 19th century.

In Naples, the worst reported event occurred in 1868: on February 28th, a huge volume of NYT fell from Mt. Echia (a small hill overhanging the Chiaia district) reaching, after a travel of some hundred metres, the Castel dell’Ovo and blocking the whole area for several days. On that occasion, 60 people died and tens of injuries were registered. Another event which deserves to be mentioned took place towards the end of the 19th century. A rockfall in NYT detached along the coast of Posillipo, near the Donn’Anna Palace, on New Year’s Eve of 1889. A further landslide was registered in the same area on January 11 1889, after which authorities decided to remove some unstable blocks from the cliff by shelling them from the sea. The “remedial measures” went on from January 21 to February 2, when 200 m^3 of tuff fell down the hill, hitting a building (Lenci Palace) and causing serious damages.

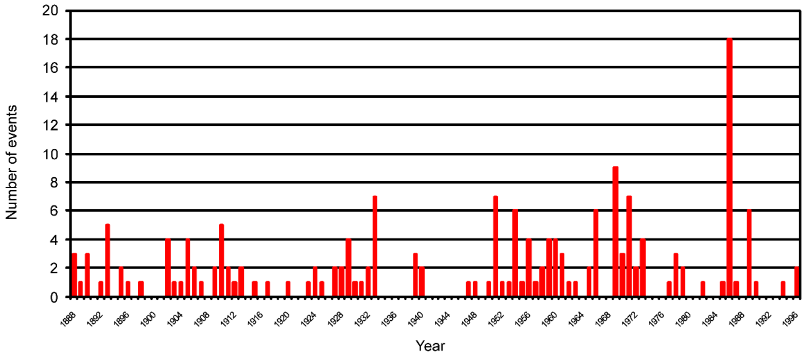
In Pozzuoli, the earliest archival information dates back to the 19th century. An English newspaper of that time reported that a rockfall occurred along the coast of Pozzuoli as a consequence of an earthquake which hit the area on October 12, 1856, even though no record was found in the official catalogues which probably indicates that the mass movement was caused by a local low-energy seism (Calcaterra *et al.*, 2003b).

Figure 66. Landslides in Naples.



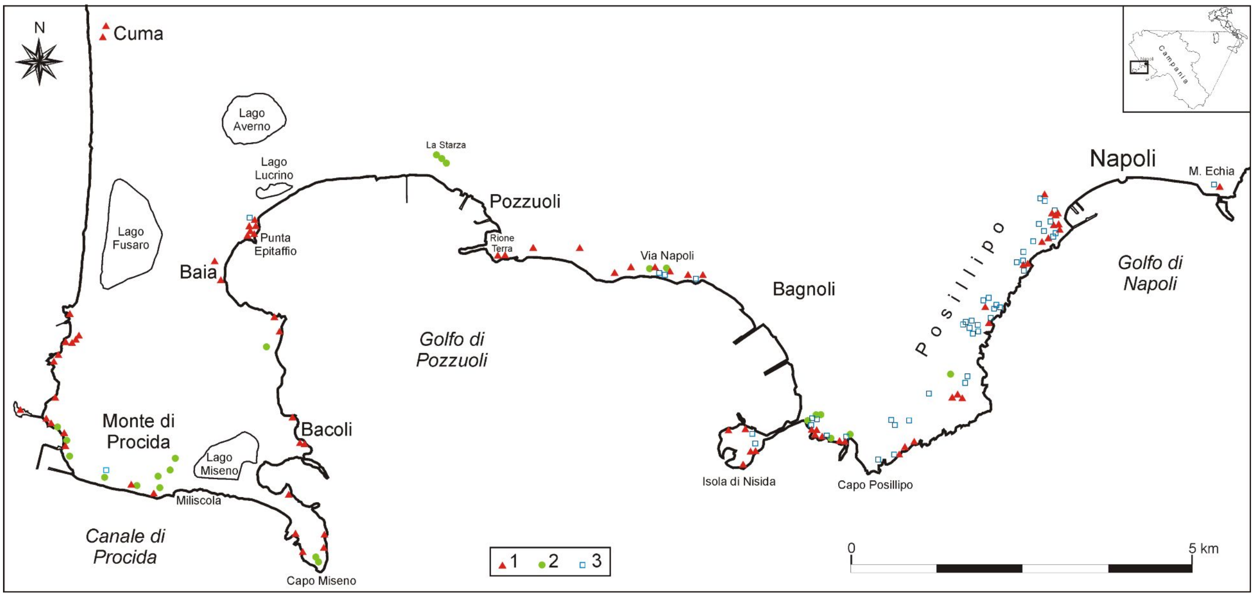
Landslides distribution in the city of Naples [after Calcaterra *et al.* (2002d), modified].

Figure 67. Landslides in Naples.



Annual distribution of the landslides in the city of Naples for the period 1886-1996 [after Calcaterra *et al.* (2002d), modified].

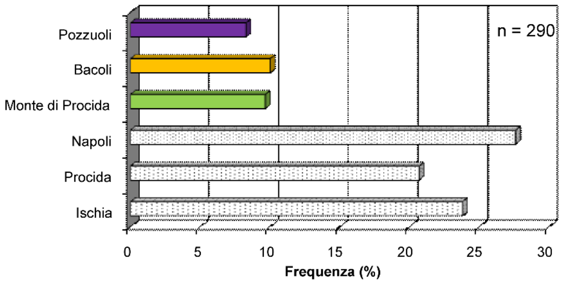
Figure 68. Landslides in the Campi Flegrei.



Coastal landslides of the continental Campi Flegrei district [after Calcaterra *et al.* (2003b), modified]. 1) Fall; 2) slide, slide-flow; 3) unclassified landslide.

As a result of the historical research on Naples, 192 landslides were identified in the time span 1886-1996, distributed over the municipal territory as shown in Figure 66, while the temporal distribution is depicted in Figure 67. The main peak corresponds to 1986, due to a major rainfall-induced episode which occurred in February and which caused a high number of mass movements in the whole of the Phlegrean area (see also Beneduce *et al.*, 1988). On the other hand, the total absence of data in years such as 1914, 1916, 1918, 1941-1946 can be explained with the presumable loss of attention paid during wartime by the media to events of local interest. In 109 cases, triggering causes were tentatively identified: rainfall events caused about 60% of landslides, 15% of which were also affected by human activity. The latter - considered alone as a triggering factor and subdivided in trenching/excavation and quarrying activity - was responsible for the remaining 40% of mass movements. Thanks mainly to articles and accompanying photographs, typology of landslides was recognized in 58% of cases. A large part of them were rockfalls; soil slide-debris flows in loose pyroclastics were identified in a limited number of cases, most of which came from Beneduce *et al.* (1988). NYT was easily recognized as involved in 69 mass movements, the remaining being ascribed to loose pyroclastics. In this case, no further distinction was made, since terminology employed by many of the sources were not clear enough. In any case, the youngest pyroclastic deposits clearly have hosted a large number of events (including top-soil and landfills). Even if information is scarce regarding the volumes of material mobilized, much more detail can be found to account for property damage and human casualties caused by landslides. Roads, private houses, retaining walls, and vehicles are the typical elements involved in a huge number of landslides. Eighty of them caused deaths or serious injuries to people. In total, 191 human lives were lost in Naples by mass movements, and some hundreds of injuries were counted.

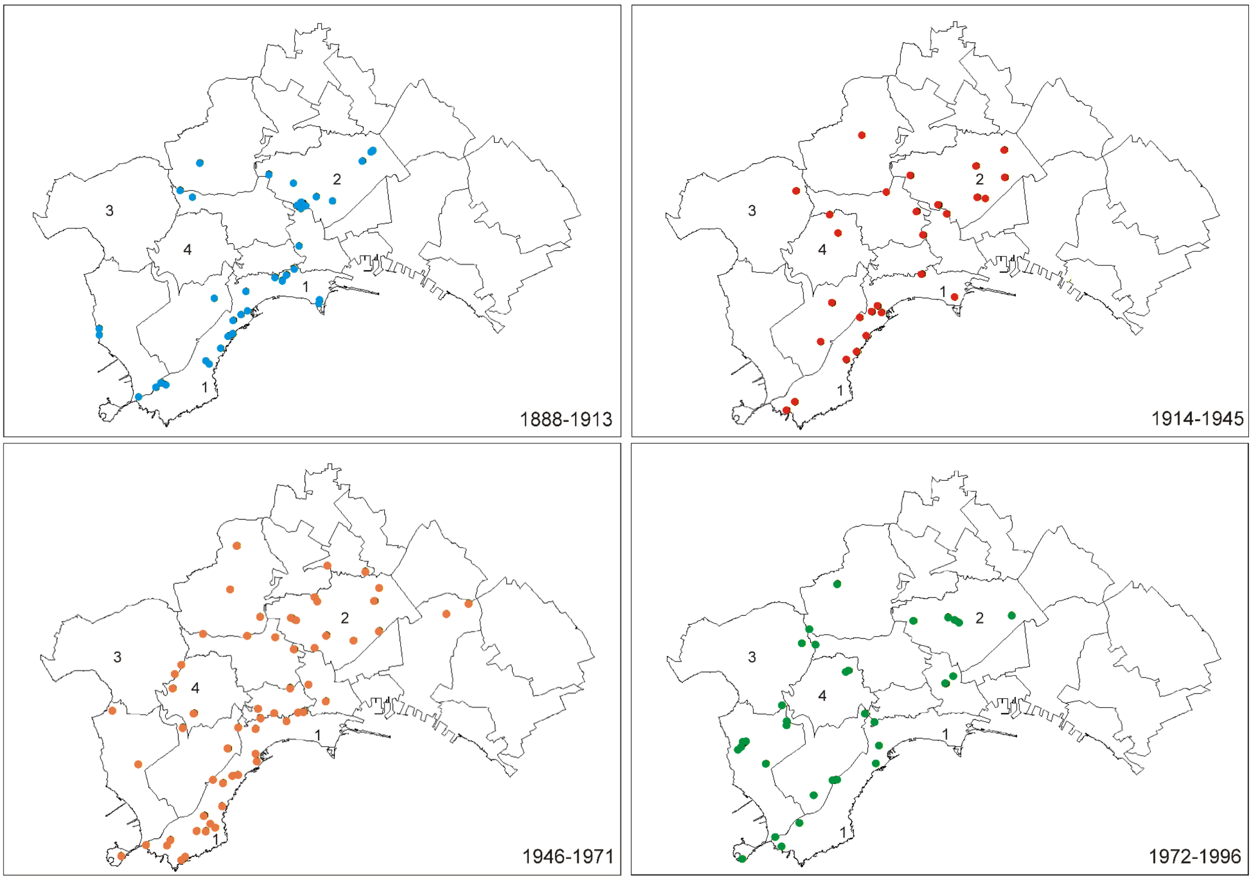
Figure 69. Landslides in the Campi Flegrei.



Frequency distribution of coastal landslides over the Campi Flegrei territory [after Calcaterra *et al.* (2003b), modified].

The research on historical landslides has been extended to the shoreline of the Phlegrean district, including both the continental sector and the islands of Ischia and Procida (Fig. 68; Calcaterra *et al.* 2003b). As regards the Phlegrean municipalities located west of Naples (Pozzuoli, Monte di Procida, Bacoli), 80 events were inventoried, dated between 19th century and 2001 (Fig. 69). Falls detached from the Yellow Tuffs and slide-flows in the youngest loose pyroclastic deposits are the prevailing typologies which have repeatedly affected the road connections along the Phlegrean coast, sometimes resulting in serious consequences. This was the case of a rockfall that occurred on November 1970 in Pozzuoli when a couple of blocks, 10-12 ton in weight each, landed on a Naples street, killing two people.

Figure 70. Landslides in Naples.

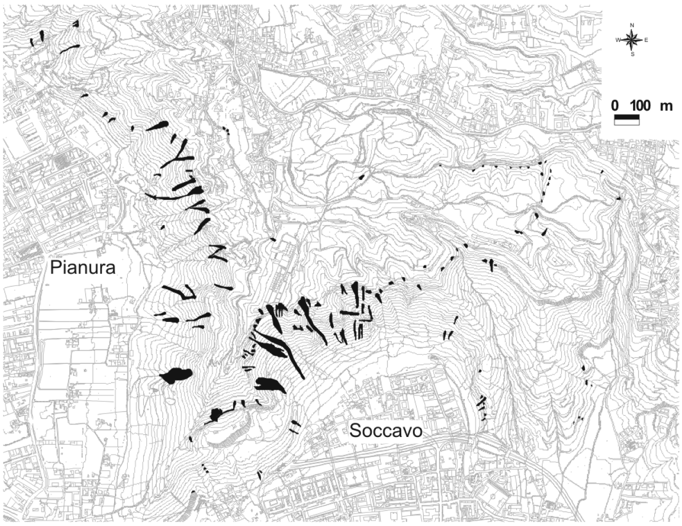


Temporal landslide distribution in the city of Naples. 1) Borough of Posillipo; 2) borough of Stella-S. Carlo all’Arena; 3) borough of Pianura; 4) borough of Soccavo.

Notwithstanding the long history of Phlegrean slope instability, the turning point in public awareness of the threat was represented by the regional geomorphic crises which hit the Campania region from 1996 to 1998. The worst of all these events was the one which involved Sarno and four other towns in the carbonate Apennine (160 victims). In Naples and in the Phlegrean municipalities, a huge cluster of landslides took place in the 1996-1997 winter, with an absolute peak on January 10-11, 1997. Calcaterra and Guarino (1999a, b) described the basic features of that event at Naples, when more than 300 shallow landslides, mostly of the soil slide-debris flow type, involved essentially the loose pyroclastics younger than 15 ka, causing severe damages to man-made structures. Comparing the historical data available for Naples with those commented by Calcaterra and Guarino (1999a, b), it can be highlighted that landslide distribution shows a sort of “migration” from some districts to other ones: if in the past Posillipo and Stella-S. Carlo were more frequently involved in slope instabilities (Fig.

70), during the January 1997 event the highest number of landslides was registered along the slope of the Camaldoli hill, falling for a great part within the districts of Pianura and Soccavo. Provided that most of these phenomena were induced by rainfall, the tentative explanation of the cited migration could relate more to human impact on slope stability. At Posillipo, in fact, in the period up to the start of WWII, important infrastructure and buildings were being constructed. Furthermore, most of the NYT urban quarries were open within the boundaries of Stella and Posillipo. Dell'Erba (1923) mentions about 25 sites where NYT exploitation was active in both districts. On the contrary, the Camaldoli hill was extensively involved in urbanization in second half of the 20th century.

Figure 71. Landslides in Naples.



Location of the main landslides occurred on the north-western (Pianura) and south-eastern (Soccavo) sides of Camaldoli Hill between 1996 and 2006 [after Calcaterra *et al.* (2007a), modified].

The incidence of Camaldoli landslides, compared with the total number of events in Naples has substantially increased in recent times. In fact, between 1868-1996 only 15 of the inventoried landslides involved the Camaldoli slopes, while, from 1996 to August 2006, about 150 mass movements were identified along the Camaldoli slopes (Fig. 71) of a total number of about 400 mass movements recognized in the same period at Naples. Among the recent landslides, slides are the prevailing typology, as simple movement or as initial component of complex events, which evolve into debris flows; such landslides primarily involve the post-NYT loose pyroclastic terrains. Falls detached from lithified tuffs are also typical of the Camaldoli slopes, which can again trigger flow-like movements. The majority of Camaldoli landslides, as well as in the whole Neapolitan territory, do not exceed 1 m in depth. Slope angles in the source areas vary widely. Whilst falls move as usual from slopes with angles greater than 60°, in the case of the slide and flow types the highest number of events (69%) occur at values between 30° and 55° (mean value: 45°), with an overall frequency pattern which shows a Gaussian distribution.

Along the flanks of Mt. Somma-Vesuvius, the main slope instability type is represented by floods. In this respect, it is interesting to note that local populations refer to these events as *lave* (lava flows), which clearly reflects their high mobility and destructive action. In volcanic regions, a certain confusion persists when mass flows involving pyroclastic deposits have to be defined. The most popular term is probably "*lahar*", an Indonesian word that describes a hot or cold mixture of water and rock fragments flowing down the slopes of a volcano and (or) river valleys (http://volcanoes.usgs.gov/hazards/lahar/index.php). However, scientists often use more specific terminology to describe properties and behaviour of lahars, for example: mudflows, debris flows, hyperconcentrated flows, cohesive and non-cohesive flows. The worst Vesuvian lahars followed the A.D. 79 and the December 1631 eruptions. In more recent times, the products ejected during the April 1906 eruption fed a number of slope instabilities, especially along the western side of the volcanic edifice, which caused serious damage to the towns of Pollena Trocchia, Cercola and S. Anastasia (Mercalli, 1906; AA.VV., 1999; Carlino, 2001).

Underground cavities

The presence of underground cavities in urban areas can have serious consequences for man-made structures, sometimes leading to their sudden collapse. In the Phlegrean district, this has been the case since the first evidence of human presence and activity, which goes back to about 4500 yrs. B.C. In fact, one of the oldest archaeological findings is a couple of Neolithic underground tombs (the so-called "Gaudo culture") discovered in 1950 in the Materdei district, Naples, which were carved in the NYT (Albertini *et al.*, 1988).

The expansion of the first communities, which started in the 5th-4th centuries B.C., was accompanied by an increasing demand for building materials, but also for underground spaces. Catacombs, conduits, aqueducts, cisterns, food and beverage repositories have been continuously dug in the subsoil of the Phlegrean towns through the centuries. During World War II, the same caverns (more than 200) were used as air raid shelters, while in more recent times some of them have been further adapted (parking garages, warehouses, illegal waste disposal sites, even a theatre-cinema) and nowadays represent one of the main tourist attractions all over the district (Fig. 11b).

A few years ago, the Naples provincial government carried out a survey of all the province's municipalities (with the exception of Naples) which revealed that the subsoil of 39 municipalities (out of 92) is characterized by the presence of underground cavities (Provincia di Napoli, 2002). 1965 cavities have been inventoried, 881 of which have been directly surveyed, showing an area of about 254,000 m^2 and a volume of about 1,400,000 m^3. All three Phlegrean towns west of Naples (Pozzuoli, Bacoli, Monte di Procida) are populated with underground openings; however, only 31 cavities are known, most of which are of archaeological interest.

On the contrary, Naples is the capital of the province as regards the cavities, as well. In fact, no fewer than 500 underground openings are known in an area covering about 620,000 m^2 (Albertini *et al.*, 1988). The most interesting of them is probably represented by the network of conduits, pits and cisterns created for the Roman aqueduct, which brought water via the Aqua Augusta, historically referred to as the Serino aqueduct; its source was in the Terminio-Tuoro massif, located some 60 km east of Naples. Several kinds of instabilities affected the Neapolitan underground voids, which have been described by Evangelista (1994). One of the most common is settling (or occasional collapse) of the ground surface above the cavity vault caused by excessive upward propagation of the quarrying activity. Even though unrelated to the specific geological setting, underground fires are also a significant problem in Naples due to the dumping of tons of waste and garbage into the voids below in recent years; such a situation has caused several fires which have burned out of control, sometimes with tragic consequences.

If NYT is the main formation affected by the cavities in Naples, some of the greatest underground openings in the city were dug in the Piperno formation which, as recalled above, represents the most widely used stone in the historical architecture of Naples. Piperno was exploited from Greek-Roman times until the beginning of the 20th century when the environmental conditions became very dangerous. One of the ancient underground quarries has been recently studied in detail (Calcaterra *et al.*, 2007a, b), which included a topographical study of the site (Fig. 32a). The surveyed quarry covers an area of about 5,000 m^2. As a whole, its development does not show any predefined exploitation scheme or any preferential direction. In addition, pillars are scattered over the area without any logical distribution, showing irregular and different shapes - evidently an indication of static fatigue causing cut off rock prisms to topple to the floor (Fig. 32b).

Conclusive remarks

Wherever in the world climate is mild, soils are fertile and seashore is nearby, humans have planned to settle down. This tendency has been emphasized in those settings where natural resources were easily available and/or ready to use, such as water, building materials, etc. These have certainly been among the primary conditions that favoured the urban growth through time in the Neapolitan district, despite the multiple sources of geohazards threatening the area: volcanic eruptions, bradiseism, earthquakes, landslides and cavity-related surface effects. The interaction among “positive” geoenvironmental factors and adverse driving forces increases with urban growth and therefore also the risk to human activity - depending on the particular geological and geomorphologic setting.

The evidence presented in this paper shows the strong correlation and conditioning of the local geology with the anthropic activities and the social and economic development of the territory. Excluding other human activity, such as agriculture, etc., which is also tied directly to the geology of the area, our attention was focused mainly on the “dependence” of architectural choices on the available territorial resources, as sharply observed by Rodolico: “*…that a blindfold geologist entering a brand new town, unknown to him, will have information on local geology just by putting a glance on the materials used in the buildings*”. All the available resources have been exploited by man since historical times. Most of them had a volcanic origin and, sometimes, were easily exploitable and workable, such as the tuff, thus becoming the fundamental element of the architecture of main and minor centres of the province. The good technical features of these rocks meant that they were in heavy use for structural purposes; outstanding examples occur in the several colonnades of cloisters of the ancient centre of Naples made up in Piperno. Obviously, whenever more precious materials were required for particular architectural elements, such as the portals of the numerous cathedrals and noble buildings, valuable imported materials were used (e.g., the Apuan Marbles).

Resources available in the territory were not only lithoid materials. Large quantities of incoherent materials such as pumices, sand and lapilli were exploited in several sites, mostly within the Campi Flegrei and from Vesuvian areas, subordinately, as raw materials for the production of cementitious mixtures. Although less important than the lithoid counterpart, these materials played a relevant role in the architectural heritage of Naples and surroundings. Pozzolana, in particular, because it made possible to obtain, much earlier than the discovery of Portland cement, hydraulic limes used to build important submerged works.

Undoubtedly the most frequently used material throughout the long history of the town and its province is the Neapolitan Yellow Tuff that has been in continuous use since Roman times. It must also be noted, however, that ignoring the well-known technical features and weaknesses of the tuff in some of the most recent urban works, anomalous (if not improper) uses have been recorded, as in the case of some external pavings that very rapidly underwent weathering phenomena, obviously because of their extremely low abrasive strength and/or the high content in pumice. A careful investigation based on laboratory tests, if not a mere bibliographical research, would have advised against the choice of a material notoriously unsuitable for such a purpose (de’ Gennaro, 2001). Since the 1990s, the use of NYT continuously decreased to the point of nearly complete stoppage, as has happened in the past for the other materials discussed in previous chapters. This decline was dictated by concerns about its exploitation - mainly with regard to environmental interest - rather than technical reasons.

On this account, one should not ignore the prospect of preserving these local stones, which were and still are so important in the history and the culture of Naples and, more generally, of the Campania region, by authorizing quarrying with modern and less invasive techniques, exclusively for restorations or for the construction of significant architectural structures. In this view, the Regional Plan of the Quarrying Activities (Regione Campania, 2006), comma 14 – Art. 89 of the Executive Rules (Norme di Attuazione) allows the quarrying of ornamental stone historical sites in protected areas (previously permitted by the competent authorities), on condition that the total area object of authorization does not exceed 1.0 Ha and 1,000 m^3 of annual production.

It is a matter of fact that, in the last century, the Phlegrean-Neapolitan area underwent apparently uncontrolled development which compromised the environment and definitely increased the hydrogeological hazard. The abandonment by farmers of the most fragile areas enhanced this decay. Nonetheless, this territory still includes innumerable landscape and cultural resources which make it unique. It is foreseeable that future generations will be sufficiently wise to preserve this resource better than what was done by their ancestry.

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The authors would like to dedicate this manuscript to two illustrious Masters of the Federico II University: Prof. Renato Sinno, whose deep knowledge on the Phlegrean subjects is still a notable stimulus for interesting discussions on topics of great scientific relevance and the late Prof. Enrico Franco, unforgettable friend and scientific guide.

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