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Stefano Carlino

Neapolitan Volcanoes

A Trip Around Vesuvius, Campi Flegrei and Ischia

Springer

GeoGuide

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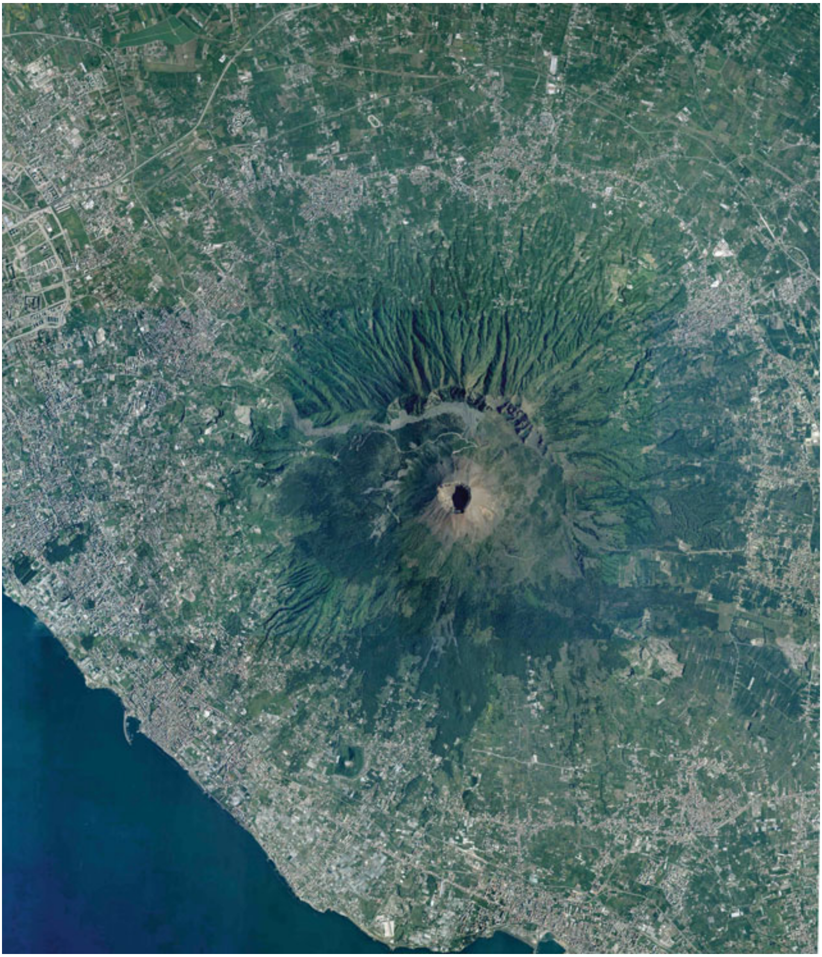

The Somma-Vesuvius volcanic complex (*courtesy* G. Vilardo, Geomatic Laboratory of OV-INGV)

The Campi Flegrei caldera (*courtesy* G. Vilardo, Geomatic Laboratory of OV-INGV)

The Island of Ischia (*courtesy* G. Vilardo, Geomatic Laboratory of OV-INGV)

Foreword

Neapolitan Volcanoes is more than a guide to the world's most exciting volcanoes: it is a story of how volcanology has grown from an entertainment for Europe's curious nobility to one of the most fascinating and challenging branches of modern Earth Sciences. It is a story, too, of how people have lived and flourished among the most resplendent and dangerous forces of Nature.

Vesuvius, Campi Flegrei and Ischia: the names alone evoke tales of the growth of European culture from Ancient Greece and Rome to the Grand Tour of the aristocracy in the eighteenth and nineteenth centuries. Even more, the consequences of eruptions can be traced back at least 40 millennia, when the eruption of the Campanian Ignimbrite, from within or near Campi Flegrei, heralded the demise of Neanderthals in Europe.

From a volcanological perspective, outbursts from Vesuvius in particular have provided the template for understanding common styles of eruption observed around the world. Most famous is the first written account of the style of explosive eruption that overwhelmed Pompeii and Herculaneum in 79 A.D., now described as Plinian in honour of both Pliny the Younger, who wrote the description, and his uncle Pliny the Elder who, as admiral of the Roman fleet, set sail from Miseno in the Campi Flegrei and died offering succour to those fleeing from the eruption. At the other extreme, sixteen centuries later the rivers of molten rock that oozed from the volcano acquired the name of lava, from the Italian verb *lavare*, to suggest that the slopes of the volcano had been washed clean.

Watching the volcanoes around Naples also reveals the importance of learning from experience. Between 1764 and 1800, William Hamilton—self-taught volcanologist and British plenipotentiary to the court in Naples—regularly hosted visitors to Vesuvius and Campi Flegrei. Writing to the Royal Society of London in 1779, he commented that he had been to the summit of Vesuvius 58 times and had visited the lower slopes of the volcano at least four times more often. Even so he says "I am not ashamed to own that I comprehend very little of the wonders I have seen on this great laboratory of Nature", adding that "yet there have been naturalists, of such a wonderful penetrating genius, as to have thought themselves sufficiently qualified to account for every phenomenon of Vesuvius, after having, literally speaking, given the volcano a *coup d'oeil*". The record shows that Hamilton's understanding far exceeded that of his guests with penetrating genius. *Neapolitan Volcanoes* follow Hamilton's principle and underline how we are still learning 250 years later.

The volcanoes today support a population of about one million people, not counting Naples, whose urban sprawl overlaps the Campi Flegrei to the west and reaches the foothills of Vesuvius to the east. Vesuvius has been quiet since 1944, Campi Flegrei since 1538 and Ischia since 1302. No one has a memory of how their local volcanoes behave. This book shows the debt modern volcanology owes to understanding Neapolitan Volcanoes and how such understanding is essential to preparing for when the very same volcanoes will come back to life.

London, UK

Christopher Kilburn
UCL Hazard Centre, University College London

Acknowledgements

This book was created with the photographic contribution of Alessandro Fedele (*Osservatorio Vesuviano*, INGV) who took many of the images accompanying the text. I would like to offer him my personal thanks for the effort spent during the writing of the book and for the passion that he showed in his work. Alessandro, who is first and foremost a researcher working in the field of geochemistry, has been able to combine his professional passion for volcanoes with the hobby of photography, capturing aspects best seen by the eye of those working on volcanoes. A special thanks goes to Paul Tout, for the English revision of the text, which has certainly added value to the significance of this book.

I would like to thank my colleagues of the *Osservatorio Vesuviano* (INGV) who, in a range of ways, contributed to the book's creation. In particular, I am indebted to the Director Francesca Bianco, who supported the idea of this book from the outset, and to my colleagues Giuseppe Vilardo, Eliana Bellucci Sessa, Gianni Ricciardi, Mauro Di Vito, Sandro de Vita, Roberto Isaia, Monica Piochi, Maria Giulia Di Giuseppe, Antonio Troiano and Angela Mormone. I am very grateful to Marina Loddo and Rosanna Altavilla, from the Library of the *Osservatorio Vesuviano* (INGV), who have always assisted me very ably in my search for the numerous articles and books required in the writing of this book. I also need to thank my IREA colleagues and in particular Riccardo Lanari, Giuseppe Solaro, Pietro Tizzani, Raffaele Castaldo and Enzo De Novellis for their contributions relating to satellite-based geophysical monitoring as well as Christopher Kilburn of University College London for his contribution to the book's preface.

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For the photographic reproductions of the archaeological and geological sites, we would like to thank the Superintendence of Archaeology, Fine Arts and Landscape for the city of Naples, the Archaeological Superintendence of Pompeii, the Archaeological Park of the Campi Flegrei and the National Park of Vesuvius.

I dedicate this book to the memory of Dino Di Mauro, a dear friend and publisher, thanks to whom I understood the importance of knowing one's own area, culture and traditions intimately.

Contents

Introduction

1

Volcanoes and their eruptions dominated the early Earth's landscape through millions of years and contributed to the birth of first primitive life. They have been responsible for the creation of the Earth crust for 4.5 billion years and led to the formation of a primordial atmosphere. It is only during the last 300,000 years that humans have gradually started to explore the world, developing their settlements for living space, shelter and food. Later, when the human society progressively developed and activities such as agriculture and farms animals were established, volcanoes and their surroundings became among the most favoured sites for human settlements as a result of the fertility of volcanic soils and the beauty of their landscapes. Nevertheless, as the world population grew, nature showed a less friendly face and humankind was confronted with adversities of various kinds including volcanic eruptions. Colossal volcanic eruptions such as that of Lake Toba (Indonesia), about 74,000 years ago, and Thera (the present caldera of Santorini, Greece), about 3,600 years ago (Figs. 1.1 and 1.2) wiped out almost all the surroundings populations, influenced human migrations and affected the global climate. Nowadays, more than 40 million people live close to hazardous volcanoes at every latitude, although large eruptions potentially threaten a worldwide population perhaps totalling more than 200 million. There are some locations on Earth where volcanic risk appears difficult for society to sustain, a situation often associated with the quiescence of active volcanoes. Despite this, quiescence, which often induces an underestimation of risk in the local population, will sooner or later be interrupted by eruptions. This is the case with the Neapolitan volcanoes in Southern Italy, where a total of about 2,500,000 people are potentially exposed to high risk of volcanic eruptions (Fig. 1.3). This book illustrates the history of these volcanoes—Vesuvius, the Campi Flegrei and the island of Ischia—their activity, their interaction with human civilisations and the risks they pose and is a trip amongst one of the world's most amazing sites, where volcanic activity has

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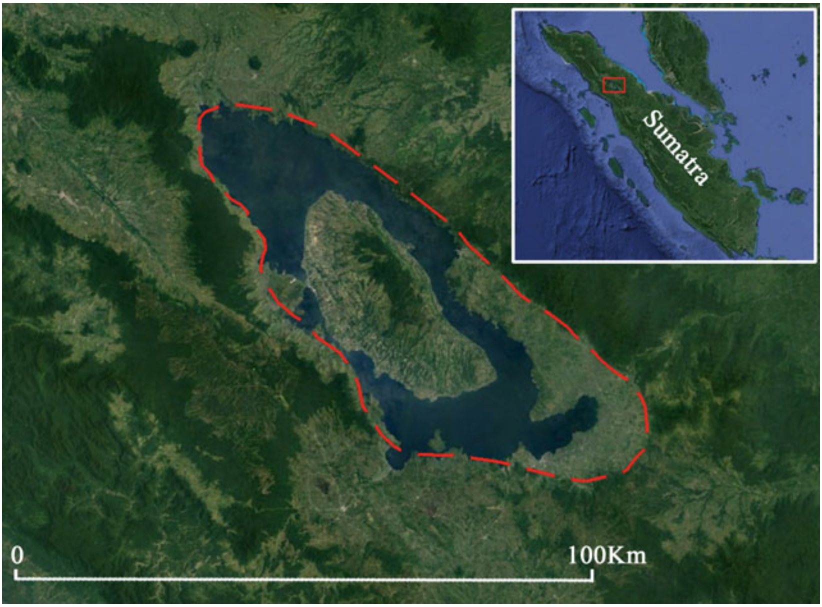


Fig. 1.1 Lake Toba, in northern Sumatra, is the world's largest volcanic caldera, about 100 $\times$ 30 km. An immense and catastrophic caldera-forming eruption, known to be the biggest eruption of the last 2 million years, occurred there about 74,000 years ago. This mega-event produced a massive injection of ash into the atmosphere, obscuring the Sun, and causing a prolonged worldwide winter. India, Pakistan, and the Gulf region were blanketed by 1–5 m of ash during the eruption which is also found in the Greenland ice-records and submarine cores in the Indian Ocean (Modified from Google Earth)

strongly influenced local culture and where Greek and Roman Civilisations were established for many centuries. For instance, once known by the name of *Pithecusa*, the island of Ischia was the site of the earliest known Greek settlement in Italy. Beneath Vesuvius, more than two thousands years later, the archaeological ruins of Pompeii, Herculaneum, Stabiae and Oplontis show an astonishing slice of human life during the Roman Empire and the devastating effects of the explosive eruptions. In the Campi Flegrei we can perceive the up-and-down movements of the ground of this large volcanic caldera, testified by the submerged ruins of the ancient Roman Harbour of Baia and by the signs left by marine molluscs on the columns of the Temple of Serapis in the town of Pozzuoli. Charles Lyell, the pioneer of the modern science of Geology, visited these sites during the 19th century, and found many important pieces of evidence that confirmed his

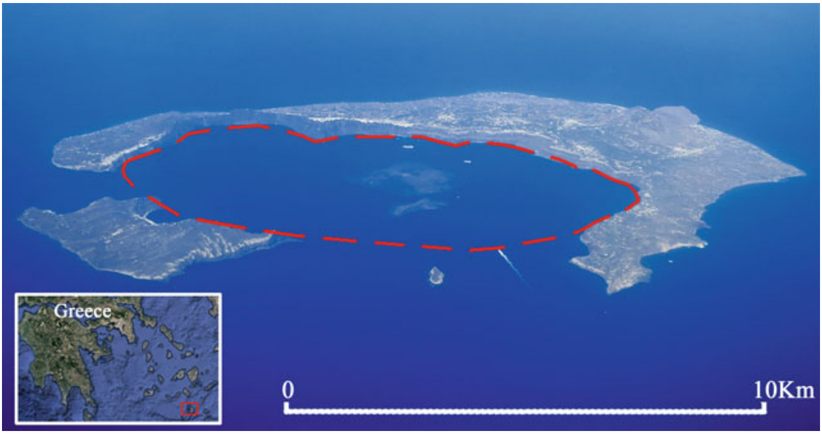


Fig. 1.2 The island of Santorini in the Aegean, fomerly known as Thera. The shape of the island is the result of a massive volcanic eruption that occurred in 1646 B.C., perhaps one of the largest ever witnessed by humankind. The explosion, estimated to be about 100 times more powerful than the eruption at Pompeii, blew out the interior of the island, forever altering its topography. Perhaps more than 20,000 people were killed as a result of the volcanic explosion (photo by Steve Jurretson)

fundamental Theory of Actualism the main statement of which is that "*the present is the key to the past*". In fact, the Earth's geological processes occur incessantly at the same rate and at all times and thus, by observing the present landscape, mountains, volcanoes, valleys, rocks and faults, geologists are able to reconstruct the past of our planet.

From a physics point of view, volcanoes represent the most spectacular expression of the heat contained within the Earth's interior. At depths of tens to thousands of kilometres, between the lower crust and upper mantle, the conditions of temperature and pressure bring about the partial melting of the rocks, which behave like a high viscosity fluid. Because of the elevated temperatures, molten rocks become less dense with respect to their surroundings and migrate upwards, along the fractures in the Earth crust, lifted by buoyancy forces. During this ascent, while the temperature remains quite constant, the decreasing pressure promotes further melting. Molten rock in the crust, called magma, may be found at relatively shallow depths (typically 5–15 km), where the buoyancy force becomes null, forming magma chambers. Magma is a complex high-temperature substance constituted by the three phases of matter: solid, liquid and gas. The solid part is in

Fig. 1.3 **a** The Campania region with an indication of the main geological features: the volcanic district of the Campi Flegrei and Ischia, west to Naples, and Vesuvius to the east (**b**); the Campania Plain, enclosed between the coastline and the yellow line **a**; the Apennine chain (**a**). On the northwest side of the plain lies the Roccamonfina volcano which is considered extinct as the last activity occurred about 50,000 years ago (modified from Google Earth)

the form of crystals of a range of minerals, and the liquid is formed by silica and oxygen atoms, with others minor elements such as aluminium, potassium, calcium, magnesium and iron. Finally, the gas phase being is composed of water, carbon dioxide and sulphur. When this complex substance migrates from the magma chamber to the surface an eruption occurs. The different eruptive styles produce distinctive volcanoes shapes. Effusive eruptions form shield-shaped volcanoes such as Etna in Sicily or the Hawaiian islands as a result of the continuous stratification of lava flows (Fig. 1.4). Explosive eruptions generate stratovolcanoes, which are formed by the entire spectrum of volcanic products fragmented and ejected from the vent. This material is called tephra. A powerful ignimbrite eruption, at the top in the energy scale, produces a very large volcanic-tectonic depression called a caldera. Volcanologists associate the eruption energy to the ejected volume, which typically increases with the explosivity of volcanoes. This evaluation is based on the VEI scale (Volcanic Explosivity Index). Non-explosive and small eruptions typically produce lava flows and very minor tephra with volumes of between 1,000 m^3 and 10,000 m^3. Moderate to large explosive eruptions eject tephra volumes of between 1,000,000 m^3 and 0.1 km^3 (100 million m^3). The larger eruptions, from cataclysmic to mega-colossal, are capable of producing

Fig. 1.4 Etna, in Sicily, is an active shield volcano (3,343 m high) mainly formed by the stratification of lava flows

tens to thousands of cubic kilometres of tephra respectively, affecting both human life at a regional level and the climate at a global scale (Fig. 1.5). The most famous examples of moderate to very large eruptions occurring in historical times were generated by the following volcanoes: Soufriere Hills (Montserrat, Caribbean) in 1995–1997, Mount Pinatubo (Philippines) in 1991, Nevado del Ruiz (Colombia) in 1985, Mount St. Helens (Washington, USA) in 1980, Mount Pelèe (St. Vincent, Carribean) in 1902, Krakatoa (Indonesia) in 1883 and Tambora (Indonesia) in 1815 (Fig. 1.6a, b). The above events caused a total of about 73,000 victims and wrought heavy damage to nearby towns. The largest known volcanic eruptions, which took place from millions to thousands of years ago, are associated with the formation of calderas. Well-know examples of this type of volcano include: La Garita (Colorado), Lake Toba (Indonesia) (Fig. 1.1), Long Valley caldera (California, USA), Yellowstone (Wyoming, USA), Campi Flegrei (Italy) and Santorini Island (Greece). There are no witness accounts of such large caldera-forming eruptions worldwide, whose occurrence can be only inferred through the studies of their volcanic deposits (tephra) and the areas they cover. This is one of the reasons for which the mechanisms leading to caldera collapse and the processes occurring during these huge eruptions are not well known. An example is the Campanian Ignimbrite eruption forming the Campi Flegrei caldera which took place about 39,000 years ago. This event ejected more than 150 km^3 of tephra and produced huge pyroclastic flows (the most dangerous volcanic phenomena) that travelled across the Campania Plain, at distance of more than 50 km from the vent. The finding of such extensive ignimbrite deposits helped volcanologists in their understanding of the eruptive mechanisms and the physics of very dangerous pyroclastic flows, fundamental in assessing the level of risk for people living in the areas surrounding volcanoes. Luckily, very large eruptions are rare because the frequency of eruptive events versus the energy involved follows a power law, meaning that the larger the eruptions the lower their frequency. In fact, observing the global eruptive history of the last 10,000 years (the Holocene geological era), it emerges that, worldwide, volcanoes produced more than 3800 events with a VEI equal to 2 (moderate) and only 6 with a VEI of 7 (colossal). Thus, despite large to colossal volcanic eruptions possibly producing victims and catastrophic damage at a regional scale, they do not represents the most hazardous of natural disasters, because of their low incidence.

Nowadays there are more than 1500 active volcanoes on the planet. They are found at every latitude and affect the life of people living in their surroundings in a range of ways. As mentioned above, volcanic activity ranges from the gentle lava flows of effusive volcanoes to colossal and very dangerous explosive eruptions. The eruption style depends on the thermal and pressure history of the magma. This,

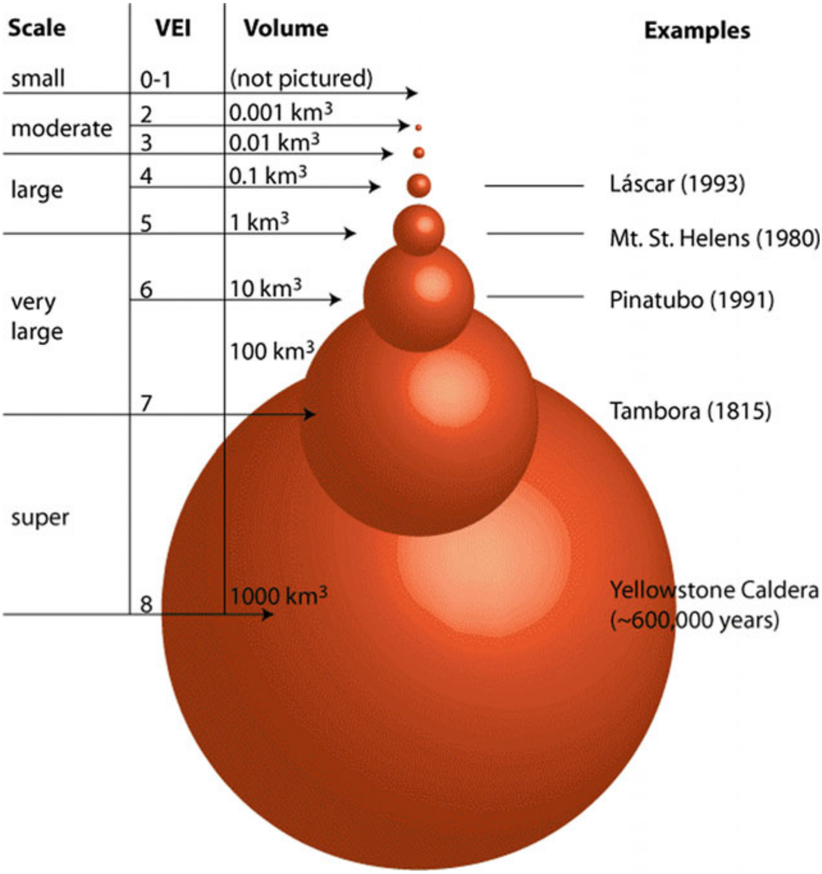


Fig. 1.5 A pictorial scale of the Volcanic Explosivity Index (VEI). This is a relative measure of the explosiveness of volcanic eruptions. The VEI was devised by Chris Newhall (USGS) and Stephen Self (University of Hawaii) in 1982. The explosivity value is inferred by quantitative and qualitative observations, such as the volume of erupted products and the height of the eruptive cloud. The scale is open-ended with the largest volcanoes in history given magnitude 8. Some examples of well-known eruptions are reported as reference to each VEI (from Newhall et al.)

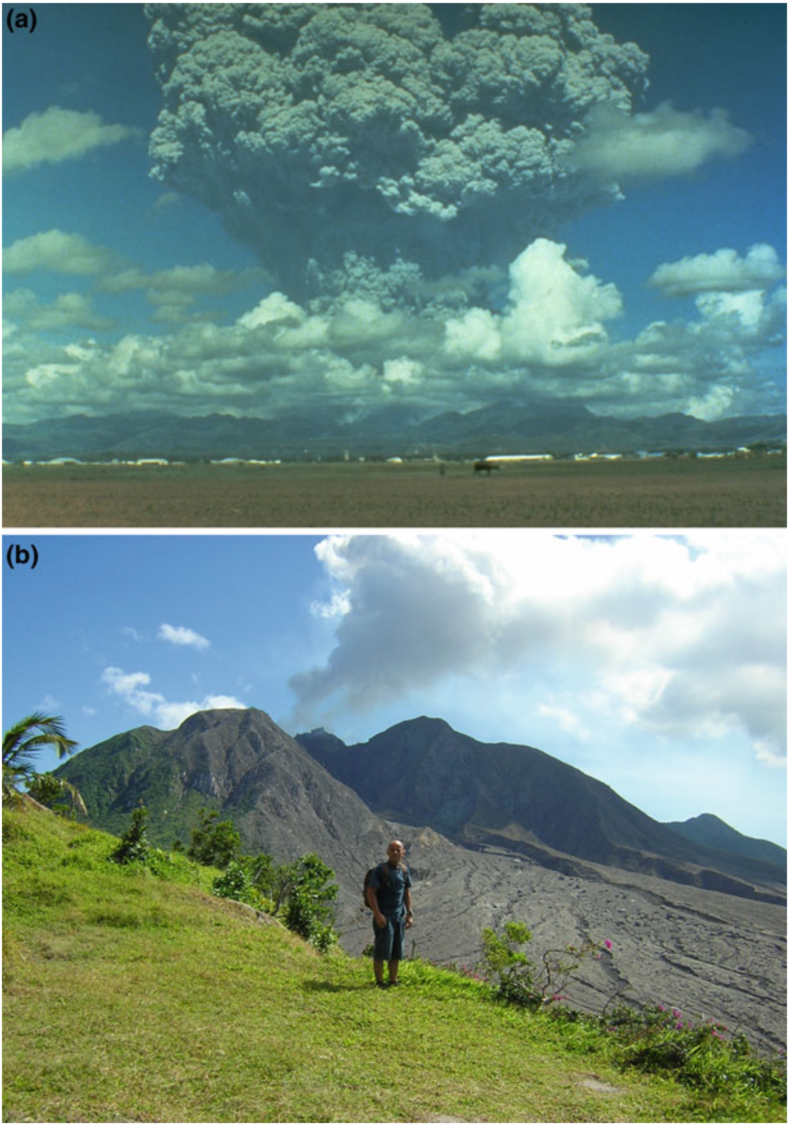


Fig. 1.6 **a** The ash column formed during the 1991 Pinatubo eruption (Philippines) (from pubs.usgs. gov); **b** the volcanic edifice of Soufrière Hills (Montserrat island, West Indies) partially demolished by the 1995 explosive eruption (photo S. Carlino)

in turn, is associated with the volcano's tectonic environment. On the scale of the energy of eruptions, the effusion of lava flow occupy the lowest levels. The lava emitted during effusive eruptions derive from basaltic magma that typically has a temperature of 1000–1200 °C, a relatively low viscosity and volatile contents together with a composition rich in iron (Fe) and magnesium (Mg) but a lower concentration of SiO_2 (Silica). When this magma rises from the chamber to the surface, it decompresses, allowing the volatile materials to form bubbles, a process known as exsolution. During effusive eruptions the volatile components are free to escape from the low viscosity magma and exsolution takes place in a gentle fashion. Most of the released energy during effusive eruptions is thus thermic. Effusive eruptions produce lava flows and sometime high lava fountains that are amongst the most spectacular of volcanic manifestations.

On the other hand, the magma feeding explosive eruptions is more viscous, has lower temperatures (800–900 °C) and higher silica and water contents and is termed "silicic". When this sort of magma rises from the chamber to the surface, the exsolved volatile substances do not easily escape from it, because of the high viscosity of the magma itself. This process increases both the magma viscosity and volume and lowers its density. At this point, the magma velocity increases dramatically, up to several hundred kilometres per hour, and the decompression process accelerates. As the magma approaches the vent, it is fragmented along the volcano conduit as consequence of the dramatic release of gases. During this process, a part of the thermal energy contained in the magma is converted into kinetic energy, ejecting volcanic products at high velocity from the vent. This is an explosive eruption, through which a gas-dominant mixture containing shattered glassy ash, crystals and pumice, is expelled from the volcano. When the discharge-rate of the eruption is sufficiently high this mixture can rise up to 30–40 km into the stratosphere, due to the buoyancy force, forming a so-called Plinian column. Pliny the Younger documented this type of volcanic activity for the first time in a written document when writing his famous letters to describe the Vesuvius eruption of 79 A.D. during which his uncle, Pliny the Elder, died.

Volcanoes also exhibit a variety of behaviours in terms of the duration of their eruptions and their quiescence periods. There are a numbers of volcanoes characterized by relatively continuous activity, the most famous example being Stromboli in the Aeolian Islands off Sicily (Fig. 1.7). Observing this volcano, the term "strombolian activity" was coined by volcanologists to describe the periodic, small to moderate lava explosions with ejection of ballistic material from the crater. This activity is associated with low risk to humans and settlements, because it affects small areas immediately around the crater. Many volcanoes, however, are characterized by short quiescent periods, typically months to years, spaced out by small effusive to explosive eruptions. Mount Etna, located in eastern Sicily, is a very good example of this type of activity. This 3,343 m (10,967 ft) high volcano periodically erupts lava from the upper craters or along radial fractures located lower down. This activity is often accompanied by the occurrence of lava fountains, due to the continuous free degassing of fluid magma. On some occasions magmatic activity on Mount Etna produces an ash column from the upper craters, when the magma, enriched with gases, increases its viscosity and enhances the fragmentation processes. The lava typically flows at maximum speed of tens of kilometres per hour, but its velocity is usually lower and does not represent a serious threat to human life. On the contrary, copious lava flows can produce heavy damage to material assets. During the eruptions of Mount Etna, the most frequent problem that people living around this volcano have to face comes from ash fall. As a result of the prevailing wind direction, the ash cloud is commonly pushed north-east of Mount Etna towards the city of Catania. Despite the concern that ash fall represents for the people—ash covers everything and penetrates everywhere and also represents a risk for aircraft—it is also a blessing for agriculture, because its high mineral content enriches the soils of the volcano and its surroundings.

Fig. 1.7 The classical, incessant small-scale explosive activity on the upper craters of the Stromboli volcano (Aeolian islands, Sicily) (photo A. Fedele)

Of the various volcanoes on Earth, dormant (or quiescent) explosive volcanoes are the most dangerous. They are characterised by relative long periods of quiescence interspersed with eruptive phases. In the last 100 years more than 70 quiescent volcanoes have produced explosive eruptions, resulting in injuries and damages. Quiescent periods vary greatly in length, from tens to hundreds or thousands years. This behaviour is strictly correlated to the dynamics of the magma chambers and plate tectonics. After explosive eruptions, the depressurizing zones below the volcano and the high erosion levels wrought by the most explosive phases can induce the collapse of volcanic conduit and its subsequent sealing. An increase in lithostatic pressure (i.e. the pressure exerted by the weight of the rocks) on the chamber can inhibit further magma ejection. In fact, the pressure inside the magma chamber may not be high enough to continue feeding the eruption and the volcano may thus enter a new quiescent phase. At that moment the residual magma in the chamber begins to cool and crystallize. Crystallisation is a very slow process, which promotes the continuous escape of magmatic fluids from the chamber.

Fig. 1.8 Fumarole activity at the Pisciarelli site, located on the eastern outer rim of the Solfatara crater (Campi Flegrei) (photo A. Fedele)

Fig. 1.9 Geothermal power plant for electric production and heating at the Krafla volcano, Iceland (photo S. Carlino)

Fluids migrate upwards into the fractured and porous rocks and reach the surface as fumaroles, gaseous discharge and geysers that represent the typical manifestations of quiescent volcanoes (Fig. 1.8). These manifestations are sometime very attractive to people, not only for their spectacular nature, but also because hot springs and fumaroles are exploited for spa and thermal therapies. Volcanoes are also exploited to produce heat and electricity from geothermal resources (Fig. 1.9). Thus, they not only produce devastation and threats, but are also a source of well-being and energy.

1.1 Naples and Volcanology

Naples is the city of Yellow Tuff. Generated by a great eruption in the Campi Flegrei about 15,000 years ago, this deposit, which has taken on the consistency of a yellow-coloured rock, is the symbol of the city, and using it this city has fed its growth. The numerous quarries and tunnels present in the Neapolitan Yellow Tuff, which show stretches of geological history, were excavated to extract building materials that go to make up many of Naples' historic buildings (Fig. 1.10a, b, c). The city, overlooking the Gulf of the same name, has grown up between two active volcanic areas, one of these, the Campi Flegrei (last eruption 1538) and the Island of Ischia (1302) to the west and Vesuvius (1944) to the east (Fig. 1.3). In this area, that today is very urbanized, the original character is still overwhelming, and geological history can be interpreted by reading the stratification of the rocks produced by volcanic eruptions. The attraction of humankind for volcanoes has ancient roots in Campania. From the Bronze Age, the first villages were built on the slopes of Mount Vesuvius, while the Græco-Roman civilisation made these places, between Vesuvius, the Campi Flegrei and Ischia Island, their favourite destination for recreation and thermal baths. Part of this long history, lasting over 3,000 years, has been sealed in deposits of volcanic eruptions that have wrought major disasters, but have left an inheritance of inestimable historical, archaeological and volcanological value for posterity. The most well-known example is the discovery of the ancient city of Pompeii, buried by the pyroclastic flows of the eruption of Vesuvius in 79 A.D.

The volcanoes are not only the protagonists of the landscape of Naples and its surroundings, but have been major players in the history of Campania and its civilisations. Volcanic activity in Campania since the Bronze Age affected the migration and displacement of the first nomadic populations, brought about continual changes in the landscape, enriched lands with minerals precious to agriculture and has attracted travellers, scientists, poets, writers and artists of every historical era. A crucial moment in the history of volcanology took place in 1631 when, after a long period of quiescence, Vesuvius awoke with a powerful explosive eruption (Fig. 1.11), beginning a long period of almost continuous eruptive activity that only ceased in 1944 at the end of World War II. The 17th century was still dominated by Aristotelian culture, but it was also the beginning of its end as a result of the works of the Galileans and Cartesians. This was a time of great cultural transformations, with new impulses in the field of scientific research coming from the introduction of the experimental method by Galileo Galilei (1564–1642). In this historical period, the mystical and dogmatic vision of the world, where the search for physical reality was independent of facts and experiences, slowly gave way to scientific interpretation of the facts based on experience. At the beginning of 17th century several attempts to understand Earth's dynamics and volcanic activity were made by various scholars, including the German mathematician and astronomer Johannes Kepler (1571–1630) and the French philosopher Descartes (1596–1650). In the theories of the time, although in a very

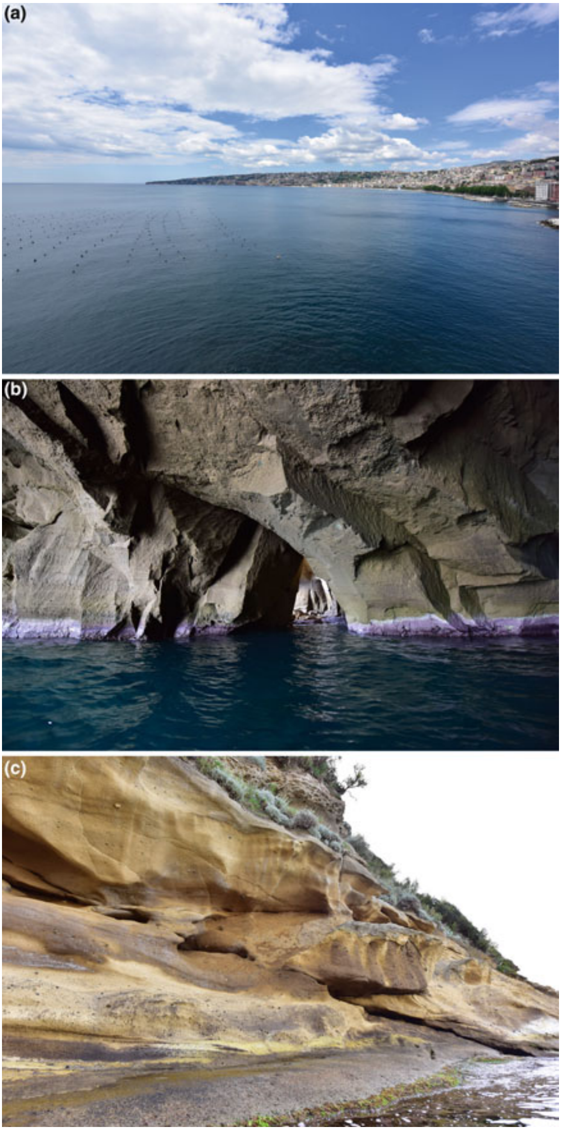


Fig. 1.10 **a** One of the most important feature of the landscape of the city of Naples is the Posillipo hill, which is entirely formed of Neapolitan Yellow Tuff and represents the eastern border of the Campi Flegrei caldera; **b** and **c** the outcropping and layering of Neapolitan Yellow Tuff along the coast at Naples (photos A. Fedele)

Fig. 1.11 A painting of the St. Januarius (= *San Gennaro*) procession in Naples, during the explosive eruption of 1631. Saints were frequently invoked during catastrophic events in Naples and the surroundings, and St. Gennaro certainly remains the most esteemed (Micco Spadaro, Processione di San Gennaro, eruzione 1631)

rough form, one can already recognize the attempt to give a physical explanation of the phenomenon, though many cases, including Descartes, still stand out for their strong dependence on the divine conception of the world. An important step came about through the thinking of the German Jesuit Athanasius Kircher (1602–1680), who, though a fervent Catholic, laid out a theory on the inner structure of the Earth the vision of which was detached from religion. The Jesuit was visiting Mount Vesuvius in 1638, where he explored the crater that had undergone profound changes after the eruption of 1631. His theory stated that the interior of the Earth was made up of a complex network of channels and that each channel, which contained either water, air, or fire, acted as a connection between the oceans, the seas and the large lakes, as a ventilation channel or for the passage of the Earth's interior fire (Fig. 1.12). In this theory one can still recognize the Greek philosophical imprint, with the primary elements, already enunciated by Empedocles (490–430 B.C.). According to Kircher, when these elements were in contact with flammable substances, such as sulphur or bitumen, earthquakes or volcanic

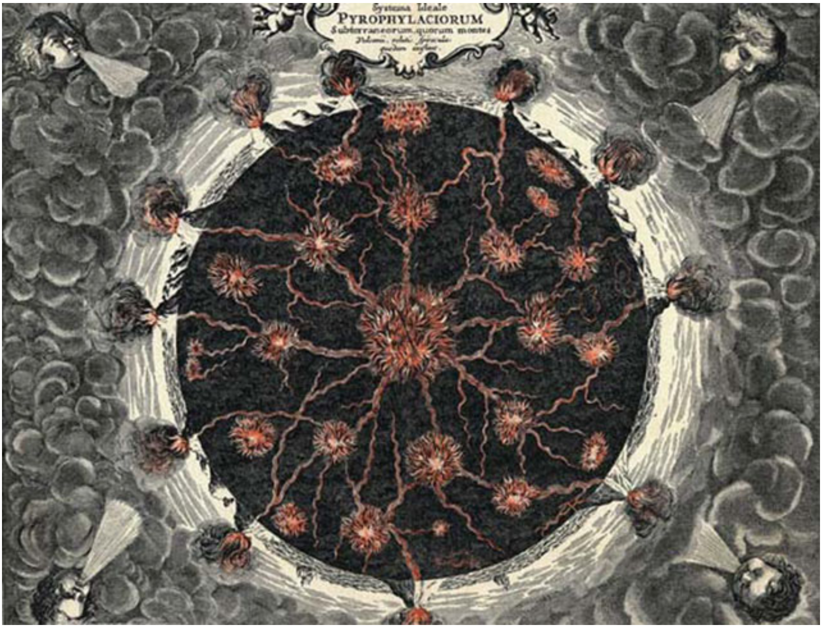


Fig. 1.12 Earth's internal fire, an illustration from an edition of Athanasius Kircher's *Mondus Subterraneus* (photos.com/jupiterimages)

eruptions could take place. Today, this theory may seem very elementary or even fanciful but it must be borne in mind that at the time there was no opportunity of experimentally verifying a hypothesis, and every idea was basically founded on the imagination. Nonetheless, Kircher's Earth hypothesis survived for over 100 years, and was also the first to predict a link between eruptions and earthquakes, which seemed to depend on a single underground mechanism.

Between the 17th and 18th centuries, Earth Sciences underwent a period of great upheaval. Firstly, geological studies and observations of volcanic manifestations fuelled the debate on the origin of rocks, finishing up at the end of the 18th century with the formation of two schools of thought, the Neptunists and the Plutonists. The former claimed that all rocks originated in the marine environment due to sedimentation, and that they are later subjected to thermal alterations, like metamorphic rocks. The latter were convinced of the volcanic origin of the Earth's rocks. The debate between the two schools of thought, often took place in bright and animated tones, especially with the advent of the Enlightenment in Europe, around the 18th century when humankind used its own intellect to free itself from previous stereotypes, employing criticism, reason and the contribution of Science.

The discussion on the origins and evolution of the Earth proved to be a fundamental moment in the studies of James Hutton (1726–1797) and Charles Lyell (1797–1875), who consecrated the transition from catastrophic theories to gradualism and actualism, in an historic period where the first centres for the study of Earth Sciences were created, with French, English, and Italian schools. Charles Lyell's *Principles of Geology*, published in 1830 (Fig. 1.13), followed on from the previous landmark in geology, James Hutton's *Theory of Earth with Proofs and Illustrations* (1788), to provide a new stimulus to the study of the dynamics of the Earth. Lyell visited Naples in October 1828, drawn by the descriptions of the volcanic rocks of the island of Ischia, set out by the geologist Gian Battista Brocchi (1772–1826) during his stay in Naples from 1811 to 1812. The Scottish geologist was also fascinated by Vesuvius and the ruins of the Temple of Serapis in Pozzuoli, where one can still see testimonies to the periods of lifting and sinking of the ground that affected the area of the Campi Flegrei. According to Lyell, active

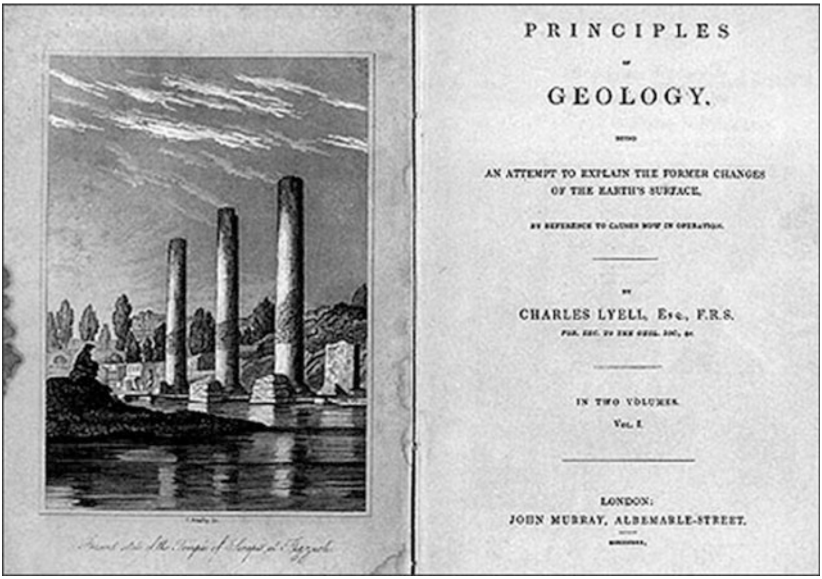


Fig. 1.13 The cover of the book *Theory of the Earth with Proofs and Illustrations* by Charles Lyell (1830), showing the Serapis ruins in the centre of Pozzuoli

volcanic areas, and their eruptive products, are of great importance in his Theory of Gradualism, which states that the causes that today produce slow changes on the Earth's surface have always taken place in the past. In Ischia, for example, Lyell observed the presence of marine fossils on some soils located at about 600 metres (2000 ft) above sea level on Monte Epomeo, showing, with the help of the Neapolitan naturalist Oronzo Gabriele Costa (1787–1876), that the island had undergone substantial and relatively recent lifting in its central sector.

The incentive for research in the field of geology has also come about from the need to identify natural resources, especially in the energy field, to meet the growing demand created by industrial development in Europe and Italy at the beginning of the 20th century and the rise in the price of oil in the 1970s. In this social context, Campania's active volcanoes have become the world's largest volcanology lab, with greatest geological minds irresistibly attracted to the continuous activity of Vesuvius and the extraordinary volcanic landscapes of the Campi Flegrei and Ischia. Already back in the 17th and 18th centuries European aristocrats used to complete their cultural education with a trip, the Grand Tour, which featured Naples and Vesuvius among its most important stops. This tradition has greatly enriched the collection of witness accounts, writings, studies and observations on the activity of Naples' very own volcano.

A crucial visit took place in 1764, when Sir William Hamilton (1730–1803), (best known to British readers as the unfortunate husband of Emma Hamilton, Lord Nelson's mistress), arrived in Naples as the British "Envoy Extraordinary to the Kingdom of the Two Sicilies". Hamilton, produced a great volume of written observations regarding the eruptive activity of Vesuvius, and did so in a systematic and rational manner that is commonly taken to represent the birth of modern volcanology (Fig. 1.14). Hamilton's amateur activity also inspired the intuition of active volcano surveillance and later, in 1841, the first volcanological observatory in the world was founded, the Vesuvian Observatory. This was a moment of glory for the Neapolitan School of Volcanology. Between the 19th and the beginning of the 20th centuries, during a period of persistent eruptive activity, a series of fundamental studies in the field of seismology and volcanology were conducted systematically on Mount Vesuvius by Macedonio Melloni (1798–1854), Nicola Covelli (1790–1829), Teodoro Monticelli (1759–1845), Luigi Palmieri (1807–1896), Arcangelo Scacchi (1810–1893), Giuseppe Mercalli (1850–1914) and Henry James Johnston-Lavis (1856–1914). In the field of volcanology, these studies were mainly be based on the collection and analysis of rock samples and constituent minerals, which contain information on the origin and evolution of magma that has traversed the Earth's crust. The approach to the study of volcanology was therefore mainly based on mineralogy and petrography together with

Fig. 1.14 Interior view of the crater of Mount Vesuvius before the 1767 eruption. Hand-coloured engraving in Sir William Hamilton (*Campi Phleraei*, 1776) (INGV-OV Archive)

visual observation of the eruptive phenomenon. By the middle of the 18th century mineralogical studies had become more systematic, the main crystalline phases had already been described, which proved useful in defining the nature of Vesuvian rocks. An initial contribution to this came from Ferdinando Galiani (1728–1787) who published the *Catalogo delle materie appartenenti al Vesuvio* (the Catalogue of materials belonging to Vesuvius) in 1772, while the subsequent studies of J.B. Louis Romè De L'Isle (1736–1790), Scipione Breislak (1750–1826) and William Thomson (1824–1907) went on to form the basis for the first hypothesis of the genesis of Vesuvian magma. In the 19th century, Vesuvian mineralogy was in its Golden Age, with crystallographic studies and the development of new techniques of physical and chemical research developed by René Just Hauvy (1743–1822) and with the systematic research of Arcangelo Scacchi (1810–1893), Teodoro Monticelli (1759–1845) and Nicola Covelli (1790–1829) at the Institute and Museum of Mineralogy at the University of Naples. At the same time, attention was also given to geology and the study of volcanic deposits, with the work by Henry James Johnston-Lavis in creating the geological map of Vesuvius and of Monte Somma, work on which went on from 1880 to 1888.

Another important contribution to the understanding of volcanic phenomena in the Neapolitan area was provided by the geologist Giuseppe De Lorenzo (1871–1957), particularly on the Phlegraean Islands of Ischia, Procida, Vivara and Nisida and the Campi Flegrei. At that time, while detailed and systematic descriptions of volcanic activity at Vesuvius were being undertaken for the first time, a disordered geological literature, resulting exclusively from superficial and sometimes inaccurate descriptions, existed instead for the areas of the Campi Flegrei and the island of Ischia. As a result of the observations and studies of De Lorenzo, there was a gradual shift from a naturalistic approach in the Geological Sciences to one of a more systemic character.

In his most important work on volcanic history of the Campi Flegrei, *The History of Volcanic Action in the Phlegrean Fields*, De Lorenzo (1904) provides an exhaustive picture of the origins of the Bay of Naples and the eruptive activity of the Campi Flegrei. In particular, he concentrates on observing regional tectonics to refute the ideas already expressed by Eduard Suess (1831–1914), who considered that the Naples basin was generated by volcanic sinking. He understood that the same dolomitic rocks, which emerge at the edges of the Plain of Campania, Capri, the Sorrento Peninsula, Nola, Caserta and Monte Massico, form the deep skeleton of the Bay of Naples. De Lorenzo describes the tectonic and volcanic evolution of the area in general terms, which, during the Quaternary period, generated phases of compression and relaxation along the Apennine chain, with the formation of folds and faults, and with the sinking of the carbonate bedrock in the area of the Campanian Plain. The "skeleton" of the city of Naples, as defined by De Lorenzo and consisting of dolomitic rocks from the Triassic and Cretaceous, was covered in later eras by the products of the eruptive activity of the Campi Flegrei. This activity was divided into three main periods, the first two, the oldest, were characterized by eruptions in an underwater environment in which one can observe the products of the activity that gave rise to the great ignimbrite eruption of the Grey Tuff (Piperno and the breccias of Monte di Procida). In the third period, however, the eruptions occurred in a sub-aerial setting (Montagna Splendida, Riccio Funda, Agnano, Astroni) until the last eruption of Monte Nuovo in 1538.

At the same time that De Lorenzo performed his studies on the Campi Flegrei, another world-renowned geologist, Alfred Rittmann (1893–1980), came to Italy, particularly interested in the tectonic and volcanic evolution of the island of Ischia. Swiss-born, Rittmann can be considered among the founders of modern volcanology in Europe. After graduating from the University of Geneva, he decided to attend the principal mineralogical and petrographic schools in the world, which brought him to the Naples Mineralogy Institute in 1926, where he dedicated his research to Vesuvius, the volcanism of the area around Naples and Ischia. Through his research, Rittmann highlighted the relationships between magmatic evolution, tectonics and volcanic activity. As noted, Rittmann's efforts focused mainly on the island of Ischia. Until 1930, scholars believed that the structure of Monte Epomeo, dominating the central sector of Ischia, was a great volcano like Vesuvius. With Breislack arguing that a large but now extinct central volcano, in the distant past defined the present morphology of the island, subsequently being subject to phenomena of breakdown and marine erosion. In 1809 the geologist L.V. Buch (1774–1853), during a visit to Ischia, challenged Breislack's interpretation, claiming that by its morphology, Monte Epomeo could not be the top of a volcanic cone. Nevertheless, almost all subsequent studies, until the publishing of Rittman's work in 1930, accepted Breislack's hypothesis. Rittmann's interpretation, still supported by most researchers today, was based on the thrust of magmatic masses below the island, which would have created the phenomenon of uplift with the formation of Monte Epomeo. Rittmann defines the island of Ischia as an example of volcanic-tectonic *horst*, where the rising block of Monte Epomeo had been pushed up by the pressure of a magmatic body, located at shallow depth (laccolite) (Fig. 1.15). The interpretation of the Swiss geologist would prove crucial, as it defined the correlation between tectonic evolution, tectonic faults and fractures of volcanic origin, and interpreted the phenomena of ground uplifting and sinking as being due to the action of superficial magmatic masses. His modern vision of volcanology, hitherto conceived almost exclusively as a study of volcanic rocks, highlights the role played by tectonics in volcanic phenomenon, both locally and regionally.

Towards the middle of the 18th century with the beginning of archaeological excavations in Pompeii and in the area of the Campi Flegrei, a new push for volcanological research was provided. At Pompeii, the discovery of the ancient city and the victims buried in the 79 A.D. eruption helped to reconstruct the main phases of the eruption and its effects on people and infrastructure. In 1750, on the opposite shore of the Bay of Naples, in the area of the Campi Flegrei, the Temple

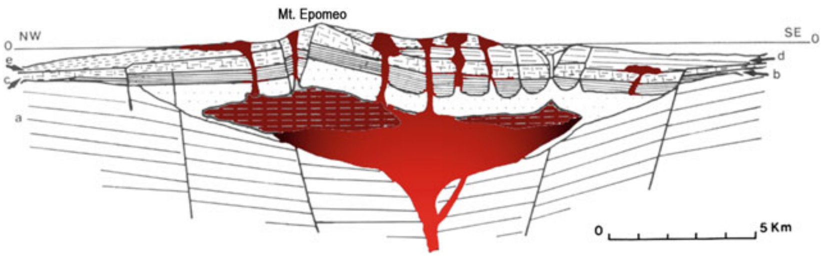


Fig. 1.15 The laccolith model proposed by A. Rittman to explain the resurgence of Monte Epomeo on the island of Ischia (Modified after Rittman, 1930)

of Serapis was discovered and the ancient Roman market, located in the centre of today's city of Pozzuoli.

Following the archaeological excavations, it was noted that the columns of the Temple bore the holes of a marine organism, *Lithophaga lithophaga*—also known as the date shell or date mussel—at different heights, indicating that the ground level had undergone subsidence and emergence when compared to average sea levels, a phenomenon subsequently termed (positive or negative) bradyseism (from the Greek βραδύς bradýs, "slow" and σεισμός seismós, "earthquake") (Fig. 1.16). Breislak's observations provided the earliest rudimentary interpretations of the phenomenon of bradyseism. These observations were followed by the studies of Edward Forbes (1815–1854) and Antonio Niccolini (1772–1850). In 1847 the British mathematician and philosopher Charles Babbage (1791–1871) published a work describing the movements of the paving of the Temple of Serapis with its uplift and subsidence phases. As a result of the then recent theory of heat conduction, carried by the physicist Jean Baptiste Joseph Fourier (1768–1830), Babbage concluded that Pozzuoli's lifting and sinking would be the result of successive heating and cooling phases due to volcanism still going on in the Phlegraean area. Later, after visiting Pozzuoli in 1845, Lyell summed up Forbes' and Babbage's observations in his edition of the Principles of Geology, supporting the hypothesis that relate bradyseism to the action of underground heat. Only in 1901 would there be a systematic campaign of investigation of submerged archaeological ruins along the coasts of Campania and Lazio, in an effort to quantify variations in sea level since Roman times and to understand what had been volcanism's actual contribution to the lifting and subsidence of the ground with respect to sea level rise and fall. The results of the studies, carried out by R.T. Gunther (1869–1940) at the beginning of the 20th century, and revised by J.P. Flemming confirmed that the estimated levels of emersion and immersion of the coastline in the area of the Campi Flegrei were due to volcanic processes and were not eustatic phenomena. Between 1940 and 1969, two fundamental contributions to the volcanic dynamics of the Campi Flegrei came from the works of Antonio Parancandola (1902–1977) and Oliveri del Castillo. The first focuses attention on possible precursors of volcanic activity and also rebuilds the curve showing the movements of the Serapis' floor with respect to sea level. The second author proposes a first conceptual model of bradyseism at the Campi Flegrei where the mechanism that generates rapid uplifting would be determined by the heating and expansion of groundwater, while the slow subsidence would be attributed to the compaction phenomena of porous pyroclastic deposits following the peripheral drainage of water. This model is in some respects still accepted by certain researchers today.

Fig. 1.16 The *Macellum*, also (and incorrectly) known as the Serapis Temple, is one of the most important archaeological ruins belonging to the period of Roman domination in the Pozzuoli area. It is a rectangular area once bordered by 36 small rooms, the shops, while on a terrace in the centre of the square stood a *rotunda*, lying in front of a *vestibule*, called the *pronao*, made up of eight Corinthian columns. The archaeological excavation of the *Macellum* began in 1750 and lasted until 1820. The central columns have been eroded by date mussels *Lithophaga lithophaga*, a species of marine mollusc, during the submerged periods, leaving us important information about the uplift and subsidence of this area. This is a very valuable archaeological and geological building as it has recorded the sea level (and ground level) variation since Roman times (photo A. Fedele)

The volcanoes were still protagonists in the study of the planet's geological phenomena in the years following the mid-20th century. During that time a profound turning point was reached in the field of volcanology when the interest of scholars no longer only focused on petrography and mineralogy, while marking the study of eruptive mechanisms and the application of the geophysical survey techniques as an aid to the understanding of the structure of the volcanoes, progressed notably. From Italy, towards the middle of the 20th century, where Vesuvius remains quiescent since 1944, attention shifted temporarily to the Philippines, where the eruption of the Taal Volcano in 1965 was interpreted using a novel mechanism described by Young for the thermonuclear explosion carried out in 1946 on the Bikini atoll (Fig. 1.17a, b). In 1971, with the conclusion of the

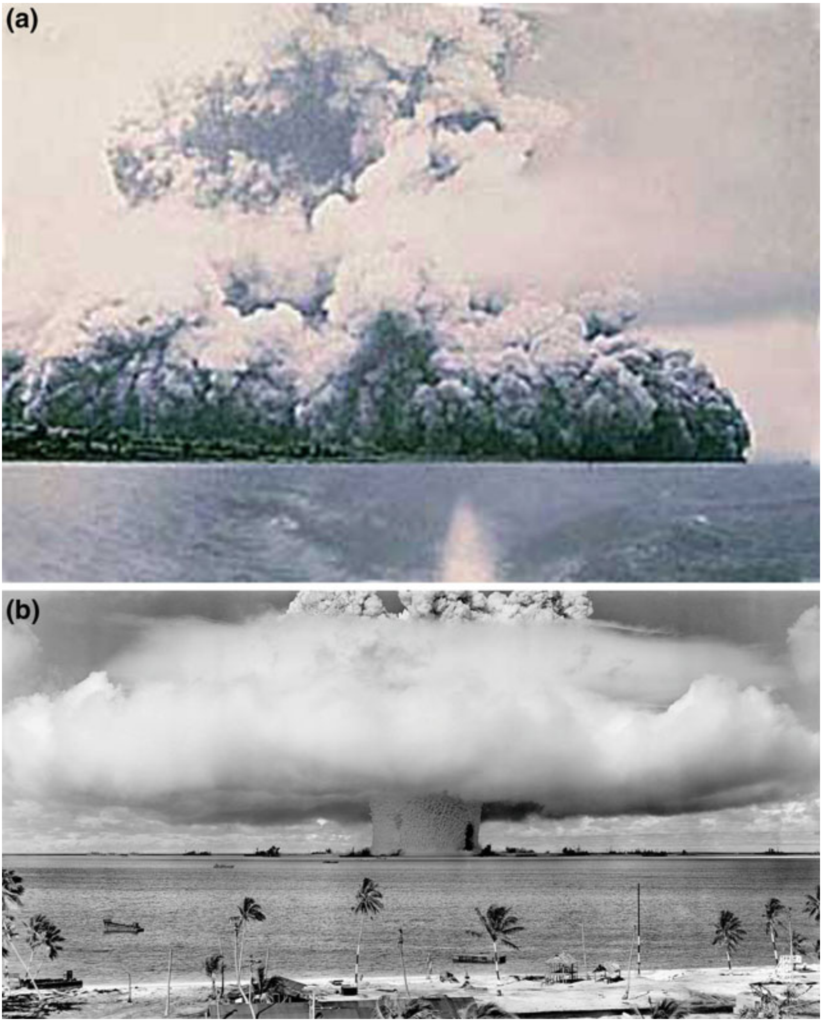


Fig. 1.17 **a** The 1965 eruption of the Taal volcano (Philippines) was the first to be interpreted using new mechanisms reported by G.A. Young for the thermonuclear explosion which took place on Bikini atoll in 1946 (**b**) (INGV-OV Archive)

Upper Mantle Project and, with the definition of the Theory of Plate Tectonics, the volcanoes remained in the foreground for the understanding of tectonic processes in the lithosphere, magma genesis and the convective currents in the Earth's mantle.

In recent times, the attention of volcanologists again focused on the Neapolitan area when, in 1970–1972 and 1982–1984, during acute bradyseism crises in the area of the Campi Flegrei, the town of Pozzuoli rose over 3 m (10 ft) with continuous earthquakes (The Vesuvian Observatory's seismic monitoring networks identified over 20,000 between 1982 and 1984) together with an increase in fumarolic emissions throughout the area. During the final phase of the Phlegraean bradyseism in 1984, the continuous earthquakes and uplifting pushed the authorities to order Pozzuoli's evacuation, not so much because of fear of an imminent eruption but because of the high level of vulnerability of buildings subjected to continuous seismic stresses. At the end of 1984, the phenomenon ceased without any eruptive events.

Increasing interest in volcanic phenomena in the Neapolitan area is also determined by the need to cope with the volcanic risk that has increased exponentially since the Second World War and today has reached levels which are no longer acceptable. For this reason, major projects will be funded, aimed at a better understanding of tectonics and volcanism in the most vulnerable seismic and volcanic areas. Among these, it is worth recalling the Finalized Geodynamic Project that, following the disastrous Irpinia Earthquake of 1980 and the bradyseismic crises of the Campi Flegrei, produced a series of in-depth studies with interesting results, particularly with regard to the areas of active volcanism of Vesuvius, the Campi Flegrei and Ischia. This increase in knowledge is also supported by the development of modern geophysical monitoring technologies, in particular those of deep seismic reflection profiling (seismic tomography). Between the end of the 1990s and the beginning of the 21st century, with the TOMOVES and SERAPIS projects, these tomography techniques were applied to the study of Vesuvius and the Campi Flegrei, allowing the identification of a low-velocity layer between eight and ten kilometres (5–6 miles) down where the magmatic basins that fuelled the great eruptions in the past would seem to be located. The results of these surveys seem to confirm the hypothesis of a rising of the Earth's mantle beneath the Naples area, which would have generated the migration of magma masses to shallow depth, thus producing districts with a high thermal gradient and widespread hydrothermal activity, in particular in the district of the Campi Flegrei and on Ischia. Recent technological developments have produced a real revolution in the field of monitoring, enabling the obtainment of more detailed information on the structure and dynamics of volcanoes. One investigative effort in the Earth

Sciences which has witnessed considerable growth with the investment of large amounts of money, is that of scientific drilling of the Earth's crust, reaching depths of several kilometres in volcanic and seismic areas and thus revealing the physical parameters of the rocks and fluids contained therein, data not otherwise obtainable using the classic methods of geophysical and geochemical surveys (International Scientific Drilling Program—ICDP). The technique of scientific investigation through the use of drilling has also been applied to the caldera of the Campi Flegrei, where in 2012, through the Campi Flegrei Deep Drilling Project, the execution of a pilot well was completed to a depth of 501 m (1673 ft) in the eastern sector of the caldera (Fig. 1.18). This project has provided new data on the volcanic history and the structure of the caldera, considered one of the most high risk volcanic areas on the planet. However, the cognitive leap in the field of Earth Sciences and the pioneering studies that have made it possible to replace obsolete paradigms with other more reliable ones (think of the drift of the continents and the establishment of Theory of Plate Tectonics) involve the last century. Today, the proliferation of data from geophysical and geochemical monitoring networks and

Fig. 1.18 Drilling into active volcanoes represents the most powerful and reliable method to get in-depth information about rock types, temperature, permeability, in situ stress and so on. The picture shows the drilling phase of the pilot hole in the eastern side of Campi Flegrei caldera, down to a depth of 500 m, carried out during the Campi Flegrei Deep Drilling Project (photo C. Serio)

the new research technologies applied to volcanoes has, in fact, been accompanied by a great many steps forward in the knowledge of the phenomenon. On the other hand, the increase in volcanic risk (not only in the Neapolitan area), driven by growing urban expansion and lack of planning controls in high risk areas, has increased the requests from both citizens and the authorities in response to the scientific community's difficulty in forecasting eruptions. To cope with the security needs of vulnerable populations, and in the absence of deterministic models able to provide certain answers, Science increasingly uses a probabilistic approach to predicting volcanic eruptions. The nonlinearity of volcanic processes makes a deterministic approach to the prediction problem impossible, while the mathematical-probabilistic expedient cannot provide a sure answer to the question: "when will it happen?"

Many of the current physical theories, not least the latest cosmological hypotheses, are based on the acceptance of the criterion that many physical phenomena are indeterministic and can only be expressed in terms of probability. In substance, by transferring this principle to volcanology, it is barely possible to give certain answers about the prediction of eruptions. On the other hand, the growth of cities and populations exposed to volcanic risk should take place while maintaining the levels of risk to within acceptable levels, so that society, when faced with a volcanic emergency, will not be forced to pay an unsustainable price in terms of loss of human lives and property.

2 Volcanic Activity and Processes

A winter view of the crater of Mount Vesuvius from Castellammare di Stabia (Photo A. Fedele)

2.1 Geological Processes and the Landscape: The Campania Plain and Its Surroundings

The "reading" of an area by geologists inevitably leads to the nature of the physical processes that shaped it. It is in the variety of the landscape of Campania that one can recognize the various geological phenomena that have been operating for millions of years in this area, located on the eastern edge of the Tyrrhenian Basin and bordered by the limestone massifs of the Southern Apennines (Fig. 2.1). The two main geodynamic processes that characterize the Miocene, from 23 to 5.3 million years

S. Carlino, *Neapolitan Volcanoes*, GeoGuide,
https://doi.org/10.1007/978-3-319-92877-7_2

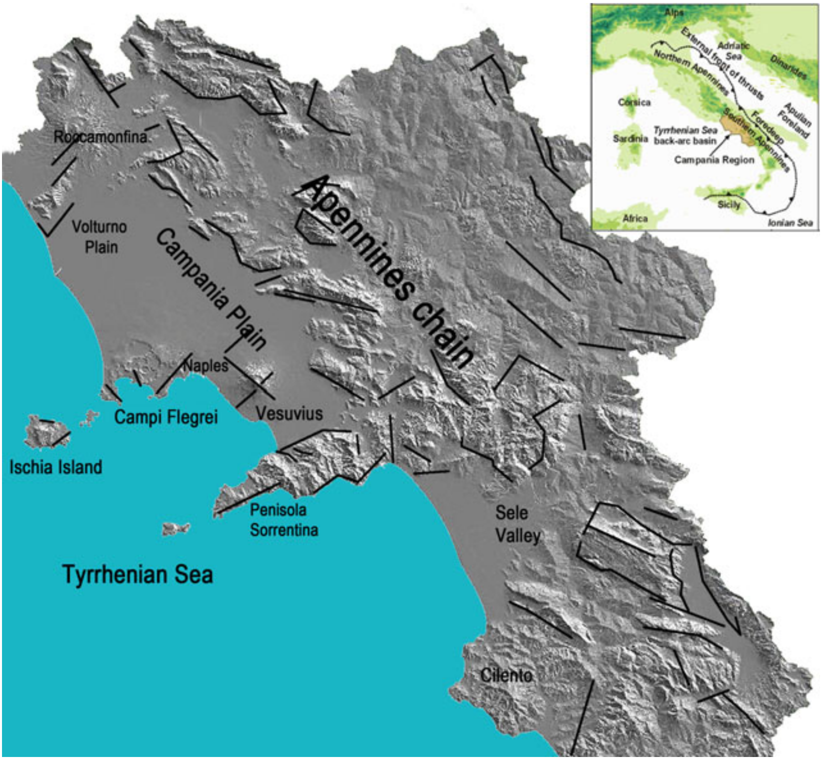


Fig. 2.1 Digital terrain model of the Campania Region with indication of the main faults (black lines) related to its Pleistocene-Holocene tectonics. The box in the right-top shows the thrust between the African and Eurasian plate that is responsible for the Apennine orogenesis (mountain building) (INGV Archive)

ago (mya), not only this area but throughout most of southern Italy, are the distension of the Tyrrhenian basin and the Apennine orogenesis (Fig. 2.2). These two processes are related to the counterclockwise rotation of the African plate to the south, converging on the Euroasian plate to the north. The border between the two plates is delimited by the Apennine chain, in the centre-south of Italy and, to the north, by the Alps, representing the zones of collision and corrugation due to convergence. The relative motion between the two plates has produced, since at least the lower Pleistocene (between 2.5 mya and 11,700 years ago), predominantly extensional tectonic activity on the Tyrrhenian side, which becomes compressive as one moves across to the Adriatic. The Apennine is a watershed between these two different tectonic areas. The Apennine rocks, which are Mesozoic-Tertiary in age, represent the ancient carbonate basement, formed in a shallow marine environment, and subsequently deformed by tectonic processes. Crustal relaxation on the Tyrrhenian margin during the Pleistocene is associated with a tectonic movement that incorporates a strongly vertical component, which caused the carbonate platform to sink as much as several thousand metres in the direction of the Tyrrhenian Sea. This resulted in the formation of *horst* and *graben* structures, which correspond to zones of upland topography and subsidence respectively. Within the setting of structures linked to the Tyrrenean distension system lies the Campania Plain which represents a *graben*, stretched in a northwesterly-southeasterly direction and filled by volcanoclastic deposits and alluvial sediments, the latter resulting from the collapse of the Apennines, for a total thickness of more than 3000 m in the area of maximum subsidence. The plain itself develops between Monte Massico to the northwest, the Campanian Apennines (the Tifatini mountains of the area around Nola and Caserta) to the east and the Lattari Mountains of the Sorrento peninsula to the southeast. Monte Massico borders to the northwest with the extinct volcano of Roccamonfina, the last eruptive activity of which dates back to about 50,000 years ago (Fig. 1.3). In the central and southern part of the plain emerge the volcanic complexes of the Campi Flegrei and Vesuvius, which together with the island of Ischia, just to the west, constitute the active volcanoes of Campania. The tectonic distension of this area, ongoing over the course of several million years, has produced a progressive stretching and thinning of the crust, with the rise of the Moho which represents the rheological discontinuity between the lower crust and the upper mantle. This process has allowed magmas in the mantle to rise through the crust, halting at a range of depths and thus feeding Neapolitan volcanism (Fig. 2.3).

From a hydrographic perspective, in the Campania Plain there are two main water courses, that of the Volturno to the north, in the province of Caserta and that of the Sarno to the south, between the province of Salerno and Naples. Between Mount Vesuvius and the Campi Flegrei runs the valley of the Sebeto (east of Naples) the course of which was excavated by an ancient river, now erased by the high levels of urbanisation and of which only geomorphological evidence remains (Fig. 2.4). The Campania Plain was also characterized by two marshy areas until the beginning of the last century. The first was formed by the eastern shores of the city of Naples, the valley of the Sebeto River and the second, a large wetland area to the west of the Campi Flegrei between Licola, Lake Patria and Castel Volturno, whose reclamation was completed after the Second World War.

For the definition of the morphology of the Campania Plain and its boundaries has therefore contributed to various geodynamic and geological processes that can

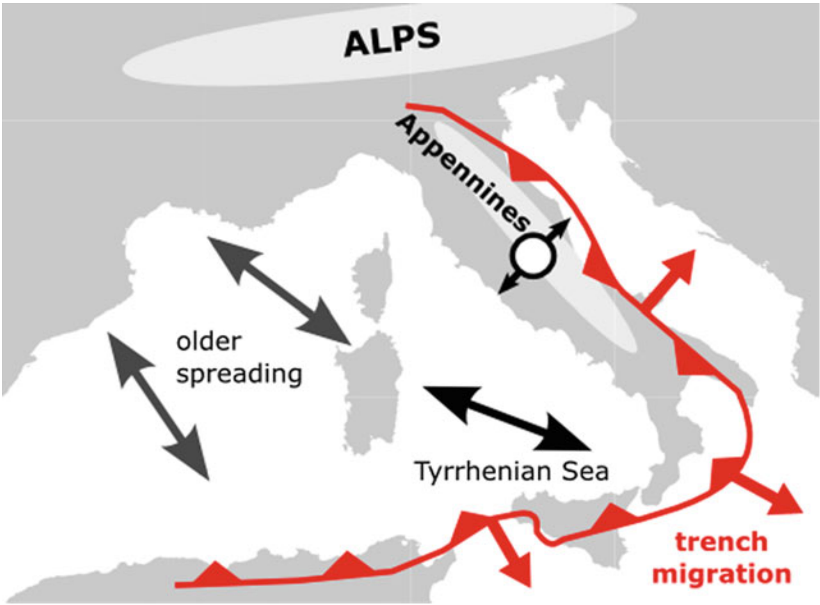


Fig. 2.2 Direction of Tyrrhenian spreading and Apennine tension along the collision zone between the Africa and Eurasian plate

be summarized as follows: (I) the tectonic distension on the Tyrrhenian side; (II) compression on the Adriatic side; (III) the rise of the Moho; (IV) river erosion and sediment transport. These processes have respectively generated: (I) the tectonic depression filled by sediments arriving from the uplifting chain and volcanic activity; (I) and (II) the folding and uplifting of the Apennine chain and its seismicity; (III) the rise of magma and active volcanism at the surface; (IV) the valley depressions and accumulation of sediments along the plain and coastline. This set of elements defines a varied and alternating landscape made up of sandy beaches, tuff cliffs, limestone crags, plains interrupted by volcanic reliefs and natural bays protected from rough seas. Starting in the north, near Mondragone, Campania is characterized by the presence of a low and sandy coast as far as Capo Miseno which lies further south, in the Campi Flegrei. The coastline here becomes higher, interrupted by small beaches, with cliffs and tuff gorges which are what remains of ancient eruptive centres of volcanic activity (Fig. 2.5a, b). After passing Capo di Miseno and its lighthouse, one proceeds on to Baia and Lucrino, with its submerged archaeological remains and the Roman *Portus Julius*, and on further south

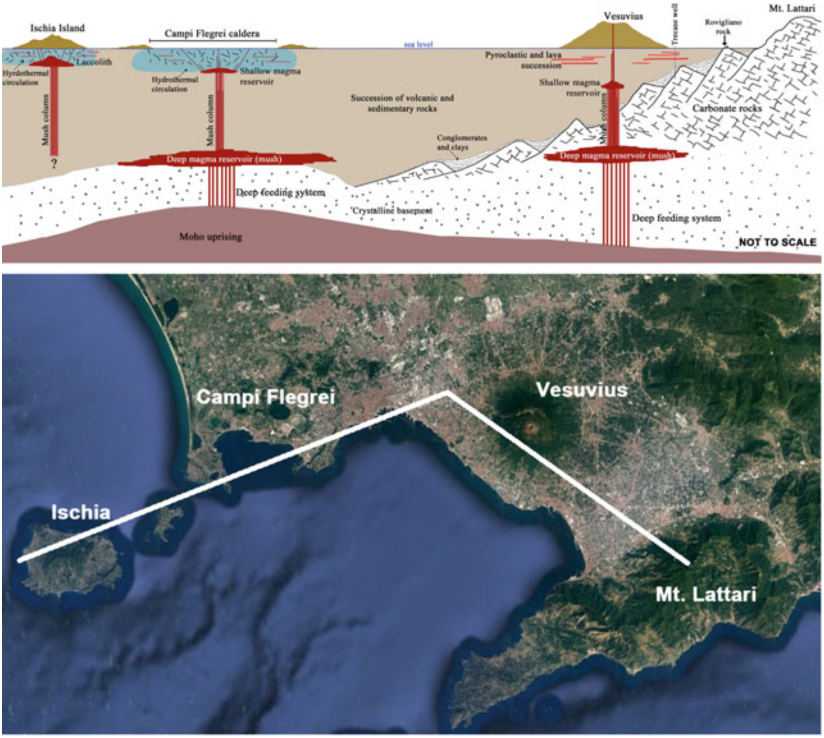


Fig. 2.3 A sketch of the possible crustal structure below the Neapolitan volcanoes reconstructed using the main geological, geophysical and stratigraphic information available. The extensional (spreading) tectonics of the Tyrrhenian basin have produced a thinning of the crust and the uprising of the Moho at a depth of about 20 km beneath the volcanoes. The minimum depth, which corresponds to the maximum stretching of the crust, occurs beneath the Campi Flegrei volcanic district that is also the area with the most intense heat flow. The extension generated intense vertical tectonic activity, with the sinking of the carbonate platform toward the sea. The deep magmatic chambers that fed the larger eruptions of Neapolitan volcanoes are possibly located at a depth of 8–10 km, which may correspond to the level of neutral buoyancy. This deeper feature has not been investigated beneath the Island of Ischia. A robust geothermal system has developed within the highly fractured rocks in the Campi Flegrei and Ischia caldera, respectively. Crystalline basement is composed of metamorphic rocks, while the zone subject to sinking was filled by volcanic and alluvial deposits during the Holocene. Conglomerates and clays may be related to the intense erosional phase and sinking of the carbonate platform in the Early Pleistocene. See also Fig. 32 for Rovigliano rock

Fig. 2.4 A map of the city of Naples during the 17th century. The red circle indicates the Sebeto River that was successively completely erased by the urbanization of the 20th century (Alessandro Baratta, 1616)

towards Pozzuoli and the Rione Terra. By now we are in the caldera of the Campi Flegrei (Fig. 2.6a, b). For thousands of years, this area has been subject to continuous rising and subsidence. The emergence of the Phlegraean caldera did not affect this area in a even fashion. The current area immediately behind the town of Pozzuoli has undergone greater upthrusting as evidenced by the sea terrace at La Starza. The latter is a volcanic-tectonic structure running in a roughly northwest-southeast direction which, starting at least 8,000 years ago, has undergone a lift of about 60 m (200 ft) as a result of magmatic upthrust. Along the coast, however, the presence of submerged ancient Roman finds and the Roman harbour itself show that this sector of the caldera has undergone a minor dislocation, remaining at relatively lower levels. The remains of the submerged Roman city near Baia can be observed both on guided tours with glass-bottomed boats, and with diving experts for those who enjoy immersions. Moving further south, one crosses the eastern eruptive centre of Nisida Island, now connected to the coast by a road-bridge, and the hill of Posillipo, the latter being considered the easternmost border of the Phlegraean caldera. The landscape in this coastal area, up as far as

Fig. 2.5 **a** During the trip with the ferryboat, from Pozzuoli to Ischia (lasting about 1 h), it is possible to obtain this view of the volcanic centre of Capo Miseno, in the Campi Flegrei volcanic district. **b** The view of Capo Miseno from the land with the village of Bacoli and its harbour. From Capo Miseno towards east extends a long sandy beach (photos A. Fedele)

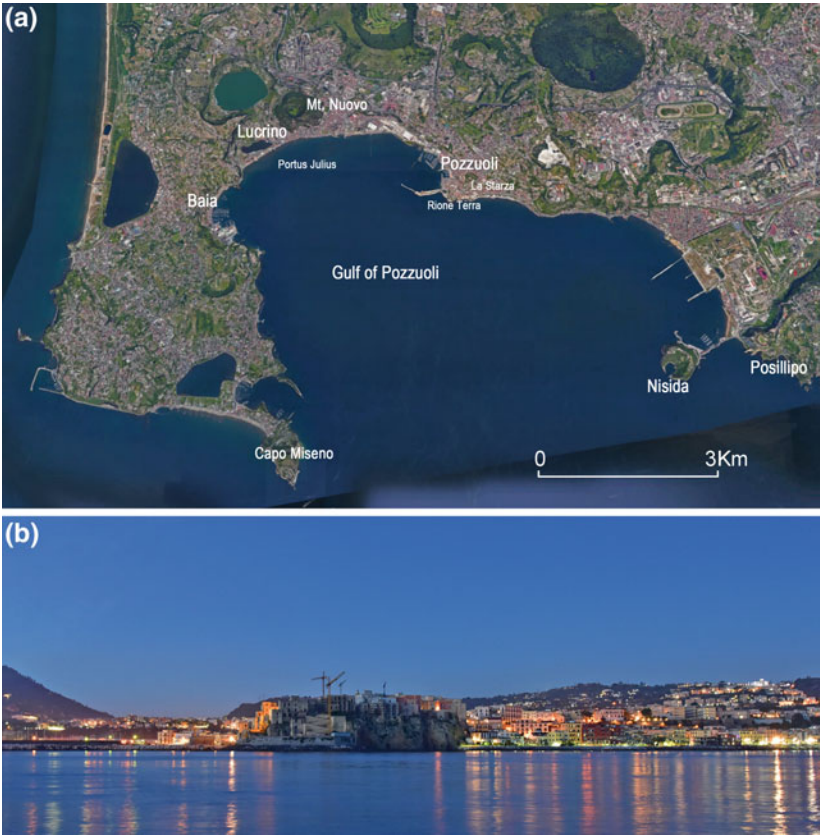


Fig. 2.6 **a** The main sites for a tour taking in volcanology and archaeology, along the coast of Campi Flegrei caldera. (from Google Earth) **b** The town of Pozzuoli with the little cliff above which stands the historical centre, Rione Terra (photo A. Fedele)

Naples, is dominated by the presence of the Yellow Neapolitan Tuff (Figs. 2.7, 2.8, 2.9, 2.10, 2.11 and 2.12). From Naples onwards, towards the valley of the River Sebeto, the coast slopes down again and remains low and predominantly sandy as far as the slopes of Vesuvius. Here the lava rocks, erupted during recent volcanic activity between 1631 and 1944, characterize much of the landscape at the southern foothills of the volcano. Continuing southward, in the direction of Torre del Greco, and observing Vesuvius you will notice that the volcano's appearance continually changes shape due to its asymmetry. This is determined not only by the

Fig. 2.7 Neapolitan Yellow Tuff forming rocks and inlets along the western coast of Naples (photo A. Fedele)

Fig. 2.8 Pyroclastic flow and surge along the *La Gaiola* site, located close to the Posillipo cape (photo A. Fedele)

Fig. 2.9 A view of the volcanic centre of Nisida from the Posillipo hill (photo A. Fedele)

Fig. 2.10 A spectacular outcropping of Neapolitan Yellow Tuff along the coast of Naples (photo A. Fedele)

Fig. 2.11 Instability in the cliffs close to Naples is not unusual as testified to by frequent rock falls along the coast (photo A. Fedele)

Fig. 2.12 The *Palazzo degli Spiriti* at Marechiaro (Naples). It represents a suggestive location belonging to the beautiful landscape of the Archaeological and Marine Park of Pausilypon (photo A. Fedele)

irregularity of the Great Cone (1,272 m /4173 ft asl), but especially by the presence of the ancient volcanic ring of Monte Somma (1,132 m/3714 ft asl), which straddles the Great Cone from northwest to southeast, leaving the structure open towards the coast. The maximum change in the shape of the volcano can be observed moving from south to north where, at the base of Monte Somma it completely conceals the view of the Great Cone, making the volcano an unusual shape compared to that typical of the gouache works and postcards of Naples. Another important morphological aspect of Monte Somma are the numerous erosion grooves, cut with a radial pattern. These structures, due to the greater exposure time the slope has been subject to erosion by rainfall runoff are almost absent on the southern slopes that are more recent (Fig. 2.13).

Close to Torre Annunziata, the coast re-enters slightly and forms a loop defining the Gulf of Castellammare, extending to the base of the Lattari Mountains. From here onwards the scenario changes yet again, moving from a flat landscape, dominated by the Somma-Vesuvius volcanic complex, to that characterized by vertical limestone cliffs overhanging deeply-cut gorges. Here we are on the Sorrento peninsula, the southern limit of the Campanian Plain which also marks the border between the province of Naples and Salerno and, towards the sea, delimits the Gulf of Naples. Here the tectonic phenomena that have affected the edges of the Campanian Plain are easily visible. The faults have dislodged the ancient carbonate platform in several blocks over millions of years, forming the current peninsula, while in the direction of the Tyrrhenian Sea, the blocks have gradually collapsed to different levels. Near the mouth of the River Sele we find the Rovigliano reef which represents the apex of a limestone block that has sunk in the direction of the Tyrrhenian while the same carbonate rocks have been found at depths of 2 km below Vesuvius during deep drilling (Fig. 2.14).

Fig. 2.13 The Monte Somma slopes area characterized by erosional structures due to the rocks' long exposure to weathering (from Nucleo Comunale Protezione Civile)

Fig. 2.14 The calcareous block of Rovigliano, outcropping along the Vesuvius' coastline. It represents a relic of the carbonate basement that sank as much as several kilometres during the Pleistocene (from Google Earth)

The Sorrento Peninsula is laid out as a long calcareous crest, in a southwesterly direction, with several massifs and highlands including the peaks of Monte S. Angelo (1444 m/4737 ft) and Monte Faito (1131 m/3710 ft.). The watershed of this limestone ridge lies to the southeast in an asymmetrical position. Consequently, the two sides, the Amalfi Coast to the southeast and that of Sorrento to the northwest, have a differing morphology. The first is narrow and steep, while the second is wider and generally with gentler slopes (Fig. 2.14). Here, too, the effects of the eruptions of the Neapolitan volcanoes can be noted. In fact, the peninsula is covered by a thin layer of pyroclastic particles (ash and pumice) resulting from the explosive activity of Vesuvius. But more surprising is the presence on the northwest side of the Sorrento basin of large deposits of Campanian Ignimbrite, resulting from the eruption of the Campi Flegrei 39,000 years ago which covered a substantial part of the Campanian Plain.

The Sorrento Peninsula ends in the southwest with Punta Campanella, from which you can see the island of Capri, also of limestone and separated from the mainland by a small stretch of sea.

2.2 The Gulf of Naples: Submarine Morphology

To fully understand the geological processes that affected the volcanic area around Naples it is necessary to look at the conformation and the tectonic structures present in the Gulf of Naples. As noted above, the Gulf itself can be subdivided into areas with different geological characteristics. The western and north-western volcanic areas, the Campi Flegrei district, Ischia and Procida; the central sector within which we find the city of Naples, predominantly formed by the yellow Phlegraean tuff that connects with Vesuvius through the ancient valley of the Sebeto River and finally the south-eastern region, where the alluvial plain gives way to the limestone cliffs of the Sorrento Peninsula. In the emergent part, the morphological structures related to the geological dynamics have, in some cases, been cancelled out by the intense urbanisation that the city of Naples has undergone in the post-war period. The geological and structural analysis of the seabed in front of the Gulf of Naples provides important information related to the tectonics and volcanic processes that have affected the area over the last one million years. In addition to the tectonic processes that have acted over long geological periods, the whole area has been subject to periods of emersion and immersion on a time scale of tens of thousands of years due to sea level variations brought about by the alternation of glacial and interglacial periods. In the Neapolitan area this is associated with the phenomena of subsidence and uplift of volcanic areas due to pressure variations within the magmatic reservoirs. During the Quaternary period (beginning 2.58 mya and continuing to the present day), volcanic activity has played a significant role in the region, significantly controlling the architecture of the sedimentary basins. The seabed is characterized by the presence of numerous eruptive centres (banks) in the area surrounding the island of Ischia, off Capo Miseno and the hill of Posillipo. The bathymetry also shows several debris avalanche deposits in the northern, western and southern sectors of Ischia and to the southeast of the hill of Posillipo. These landslides have a characteristic hummocky morphology through the presence of enormous blocks, tens of metres across, within the subterranean matrix, transported by gravity towards lower topographic areas (Fig. 2.15). The avalanche debris deposits found in the Gulf of Naples are related to the gravitational instability of the volcanic structures' slopes, often very steep and subject to continuous uplifting and deformation due to the variation of

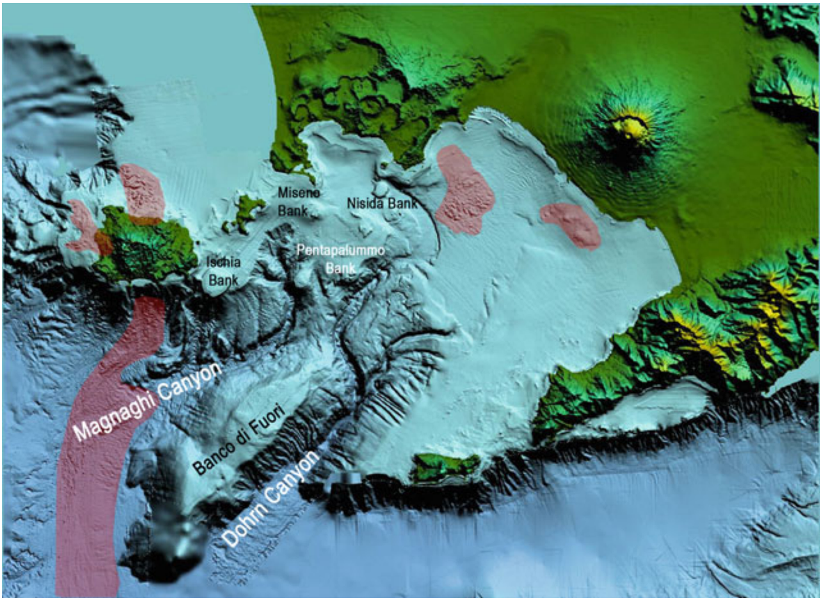


Fig. 2.15 The main structural features of the sea bed along the Gulf of Naples. Many structures are associated with submerged volcanic centres (e.g. Ischia, Miseno and Nisida Banks). The two main canyons correspond to the alignment of regional faults along the off-shore zone. The red shaded areas are the zone of dispersal and accumulation of huge debris avalanche deposits. The latter were triggered as a consequence of the instability of the steep volcanic flanks (particularly around the island of Ischia) forming characteristic deposits with a hummocky outline (courtesy Marco Sacchi from IAMC Naples)

the stress field induced by the dynamics of the magmatic sources. Such instability is characteristic of many active volcanoes on the planet.

In the northern sector (Pozzuoli Bay) the width of the inner continental shelf (0–40 m bsl) varies significantly, from 2.8 km (just over a mile) west of Pozzuoli to less than a few hundred metres at its western side (Baia). The inner sector of the continental shelf is also characterized by a series of stepped terraced surfaces located at water depth of 100, 25 and 35 m over a distance of about 4 km. Terraced areas are the result of the dynamic equilibrium between seafloor erosion and the sediment supply from the coastline during the Holocene sea level rise. The morphology of the seabed is more regular on the Naples slope (between the hill of Posillipo and Punta Campanella) with bathymetrics almost parallel to the coastline to a depth of about 150 m. The most important structural features are located offshore from the Gulf between Ischia and Capri, where there are deep valleys running northeast-southwest and north-south that drop away west of Capri in a large structure that delimits the continental shelf. The two main valleys, named after Anton Dohrn and Magnaghi, correspond to regional fault line features which develop along the main emergent volcanic structures (Fig. 2.15). The observable submarine slopes on the south and west sides of Capri and the Sorrento Peninsula are linked to the dislocations of the carbonate basement which produced the structure of *horst* and *graben*.

2.3 The Somma Vesuvius Volcanic Complex

The genesis of the Somma-Vesuvius volcanic complex took place about 400,000 years ago. In fact, this age corresponds to that measured through radiometric methods applied to volcanic rocks (lavas) found at a depth of about 1300 m (4265 ft) during drilling for geothermal purposes in the municipality of Trecase (southeast sector) (Fig. 2.16). Underlying these lavas the volcanic deposits vanish, while one encounters some 400 m (1,300 ft) of conglomerates of continental origin enriched with shallow marine fossils in the upper part of the sequence. These deposits stand on a more solid bedrock approximately 1,900 m (6,250 ft) deep, made up of dolomitic limestones from the Mesozoic era (252–266 mya) the same as those of the reliefs of the Sorrento Peninsula. Volcanic deposits are found above 1300 m (4265 ft) in depth and there is an alternation of lava and submarine volcanic products, intermixed with marine sediments, often rich in fossils. This alternation of rocks and sediments has been deposited from the Pleistocene (2.58 mya) onwards. About 400 m (1,300 ft) down, other volcanic deposits of pyroclastic nature are found (Fig. 2.16). Volcanologists have attributed these deposits to the large phlegraen eruption of the Campanian Ignimbrite which took place 39,000 years ago. Lastly, in the shallowest 250 m (820 ft) of the well the drillers encountered lava and pyroclastic products of Somma-Vesuvius, dating back to between 39,000 and 25,000 years ago. The products of activity post-25,000 years ago are found on the surface, indicating a beginning of a true construction of Somma's volcanic structure. The succession observed in the Trecase well indicates that the volcano was born in a shallow sea environment, in an area of subsidence where the *graben* structure of Campanian Plain was generated. The collapse of the plain would have coincided with a strongly erosional phase, evidenced by the presence of conglomerates of limestone origin in the stratigraphic succession of the Trecase well. The balance between subsidence and growth of the volcanic structure would have been due to the succession of tumescence and deterioration events in the area through the action of magmatic masses. This series of phenomena, the subsidence of the plain, volcanic tumescence and detumescence, and variations in the sea level, resulted in continuous immersion and emersion of the area. Post-39,000 years ago no further sediments can be found, indicating that the volcano evolved definitively in an aerial setting. This emergence therefore occurs in conjunction with the Campanian Ignimbrite eruption which deposited approximately 60 m (200 ft) of pyroclastic rocks. It cannot be excluded that the definitive passage to a continental environment may also have occurred as a consequence of a considerable uplifting which took place in the Campi Flegrei coinciding with the great ignimbritic eruption and that the tumescence due to the rise of the magma would also have had effects in the area around Vesuvius (regional tumescence). In the next, post-Campanian Ignimbrite phase, during the last glacial period (about 20,000 years ago), the sea level fell to its minimum of about –120 m (395 ft) below the present. Other data suggests that about 39,000 years ago the sea level was –80 m (260 ft) while the Campanian Ignimbrite deposit was found 120 m (395 ft) below the current sea level. This would indicate that the Trecase well area has undergone a subsidence of about 40 m (130 ft) in the last 39,000 years, a rate of about 1 mm per year.

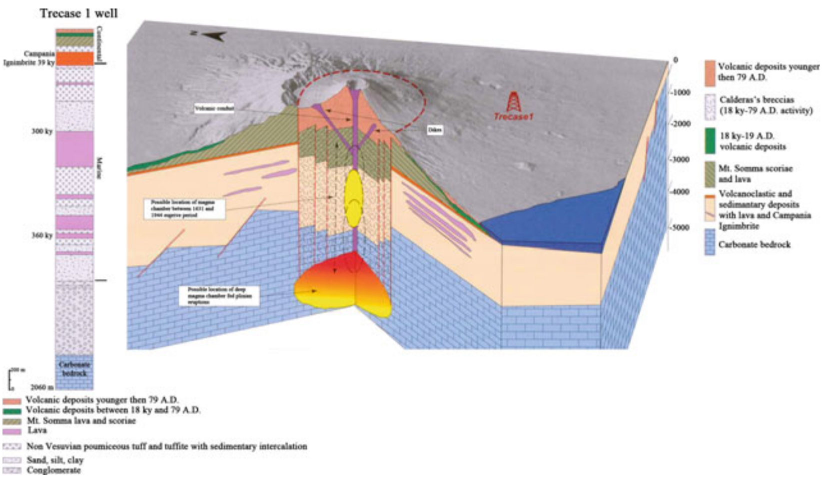


Fig. 2.16 A sketch of Vesuvius with the internal structure inferred from geophysical, geochemical and stratigraphic studies. The rock succession in the Trecase well has provided us with a better possible picture of the buried geology of the volcano (After Santacroce and Sbrana, 2003, Geological Map of Vesuvius)

The activity of the ancient volcanic structure of Monte Somma, with copious lava emissions during its primordial phase, has generated a structure with a rather broad base which was probably higher than at present. Continuous explosive high energy eruptions then demolished the volcanic cone leaving a calderic ring, Monte Somma (1,132 m/3714 ft asl) within which the Great Cone of Mount Vesuvius (1,281 m/4,203 ft asl) was formed (Fig. 2.17). The first eruption of the Somma-Vesuvius volcanic complex, recognized in the outcrop, is that of the *Pomici di Base* (Basal Pumices) (18,000–20,000 years ago). Between 18,000 years ago and the famous Pompeii eruption of 79 A.D. two other two Plinian eruptions can be identified, dating back 8,700–9,000 years (the so-called *Eruzione di Mercato*), and 3,800 years ago (the "Avellino Eruption"). The reconstruction of less energetic events in the same timespan is much more difficult. The volcano has been characterized by long quiescent periods and has given rise to a less energetic activity termed "interplinian". This activity is little known for the shortage of outcrops and survey information it has provided. The eruptive history becomes a little clearer when the first historical evidence of the Roman era appears.

We know, for example, that before the 79 A.D. eruption Vesuvius had been quiescent for at least 700 years, while the letters of Pliny the Younger on the eruption allow a comparison of the chronology of the events described and the

Fig. 2.17 The Somma-Vesuvius volcanic complex. This is formed by the ancient volcanic relic of Monte Somma which borders the younger crater of Vesuvius in the northern sector. The lava flow of the last eruption (1944), and the Colle Umberto volcanic centre (where the historic building of the *Osservatorio Vesuviano* stands) are shown (INGV-ON Archive)

geological evidence on the surface. Between 79 and 472 A.D. the volcano produced low energy eruptions, with predominantly effusive activity interspersed with periods of relative calm. In 472 A.D. when the Western Roman Empire was moving towards its definitive fall, another explosive eruption (the "Pollena Eruption") took place, it would seem to have been slightly less powerful than that of 79 A.D. Unlike the previous Pompeii eruption, the Pollena event is seldom reported in historical records, and even its dating remains uncertain. This event mainly concerned the east and north of the volcano. In the municipality of Pollena Trocchia, in an old quarry site (Carcavone) located about 5 km west of the Vesuvius crater, it is possible to observe pumices and ash more than 15 m/50 ft thick (pyroclastic flows), deposited during the explosive activity of 472 A.D. In this site it is also possible to see some interesting geological features which are associated to the presence of old lateral vents forming small scoria cones (Fig. 2.18).

Fig. 2.18 The small scoria cones in the Pollena (Carcavone) quarry (north-west Vesuvius). Highlighted are the feeder dike and the strata formed during the effusive activity. This lateral activity at Somma-Vesuvius is related to scoria-and spatter-cone forming events (of monogenetic or polygenetic nature) which occured before 22,000 years ago (photo S. Carlino)

The most detailed descriptions of volcanic eruptions are those available since 1631 when Vesuvius began persistent activity, attracting scholars and travellers from around the world. On December 16th 1631, after a period of quiescence that had probably lasted since 1139, Vesuvius awoke with an explosive eruption that left the volcanic conduit open for a long period until 1944, generating periodic lava and explosive emissions of low energy. The eruption of 1631, for which there are numerous written sources, caused serious damage to the entire southern sector of the volcano, creating panic among the population, with an exodus to Naples. The explosions decapitated part of the crater, and were accompanied by the formation of pyroclastic flows and mud slides that continued even after the paroxysal phase had finished (Fig. 2.19). Commentators estimated the number of victims at between 4,000 and 10,000. After the catastrophic event of 1631, volcanic activity was characterized by alternating flows of lava from the central crater or from lateral openings together with sporadic paroxysmal events, with a succession of 18 eruptive cycles that ended with the eruption of 1944 towards the end of World War II (Fig. 2.20). It was during this long period that the Naples volcano gained its worldwide reputation, and became the major attraction in Campania and the Italian peninsula during the Grand Tour. Following the eruption of 1944 the volcano entered a new quiescent phase, characterized by low energy baseline seismicity and modest fumarolic emissions confined to the crater area (Fig. 2.21).

Fig. 2.19 Vesuvius after the 1631 eruption. The crater was partially demolished by the explosions during the eruption (Didier Barra, *Eruzione del Vesuvio* 1631)

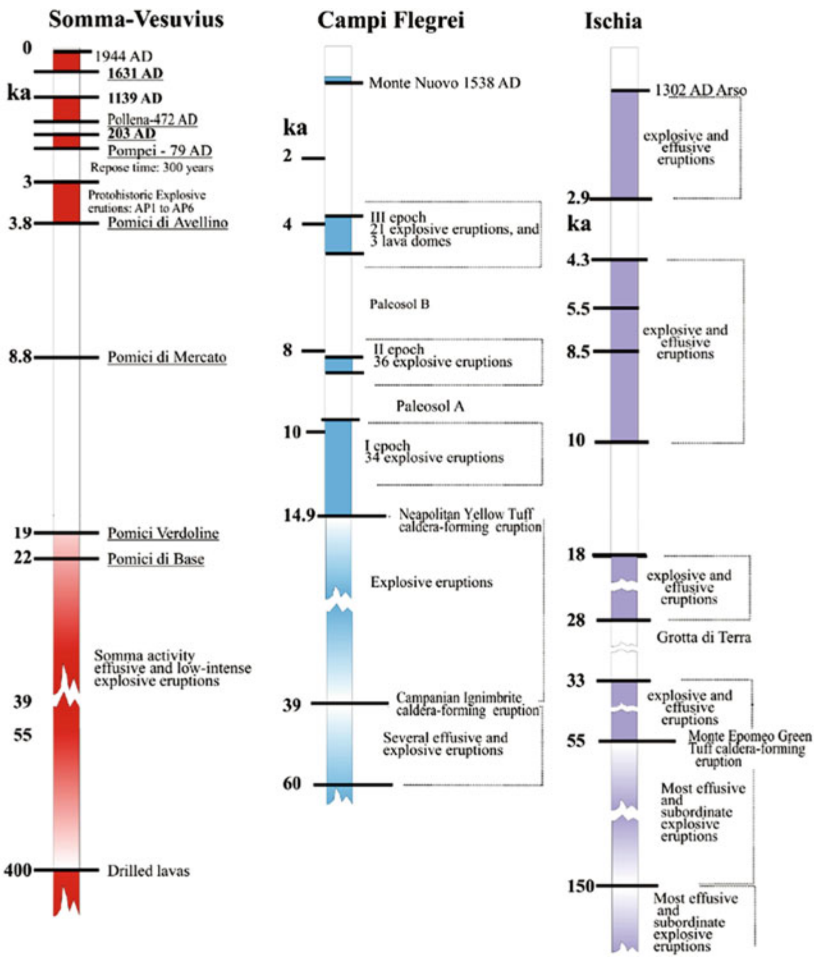


Fig. 2.20 A summary of the volcanic history of the Campi Flegrei, Ischia and Vesuvius

Fig. 2.21 Fumarolic emissions along the inner flanks of the Vesuvius crater (photo A. Fedele)

2.4 The Campi Flegrei Caldera

The Campi Flegrei caldera is part of the Phlegraean Volcanic District, which includes the islands of Ischia and Procida and the submerged vents located along tectonic structures running northeast-southwest. The southern part of the caldera is included in the Gulf of Pozzuoli and is partially submerged. Different blocks, dislocating the caldera, are the result of two major collapses, related to high-volume eruptions, and subsequent uplift. The first collapse is thought to be associated with the Campanian Ignimbrite eruption (39,000 years ago) and affected a larger area when compared to the second one caused by the Neapolitan Yellow Tuff eruption (15,000 years ago) (Fig. 2.22). The boundaries of both collapses are not well mapped, particularly in the northern part of the caldera and in the off-shore zone. In addition, the onset of volcanic activity at the Campi Flegrei is not well documented and the oldest dated outcropped volcanic rocks have yielded an age of more than 60,000 years. The erupted materials deposited during the area's volcanic history since about 39,000 years ago cover a wide area with a total volume of hundreds of cubic kilometres and are commonly tuffs. A larger part of these

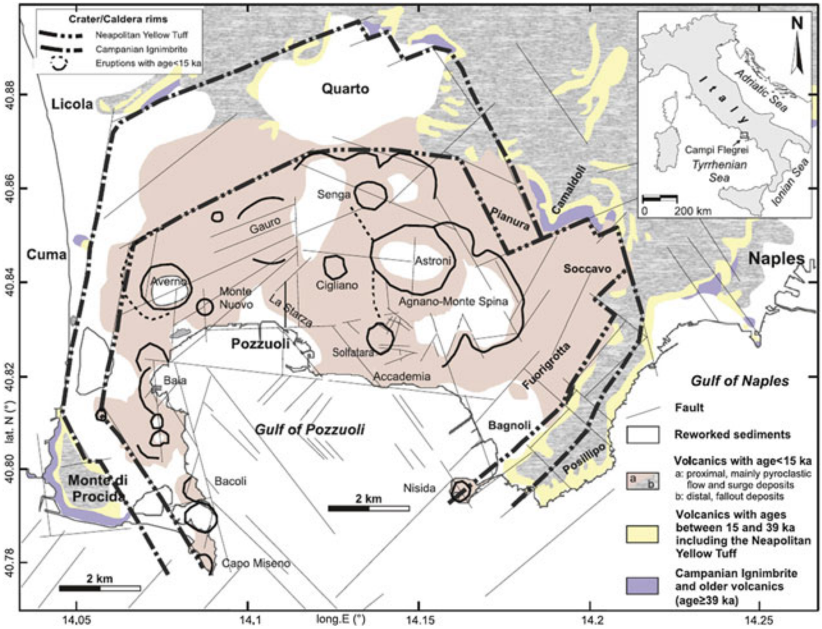


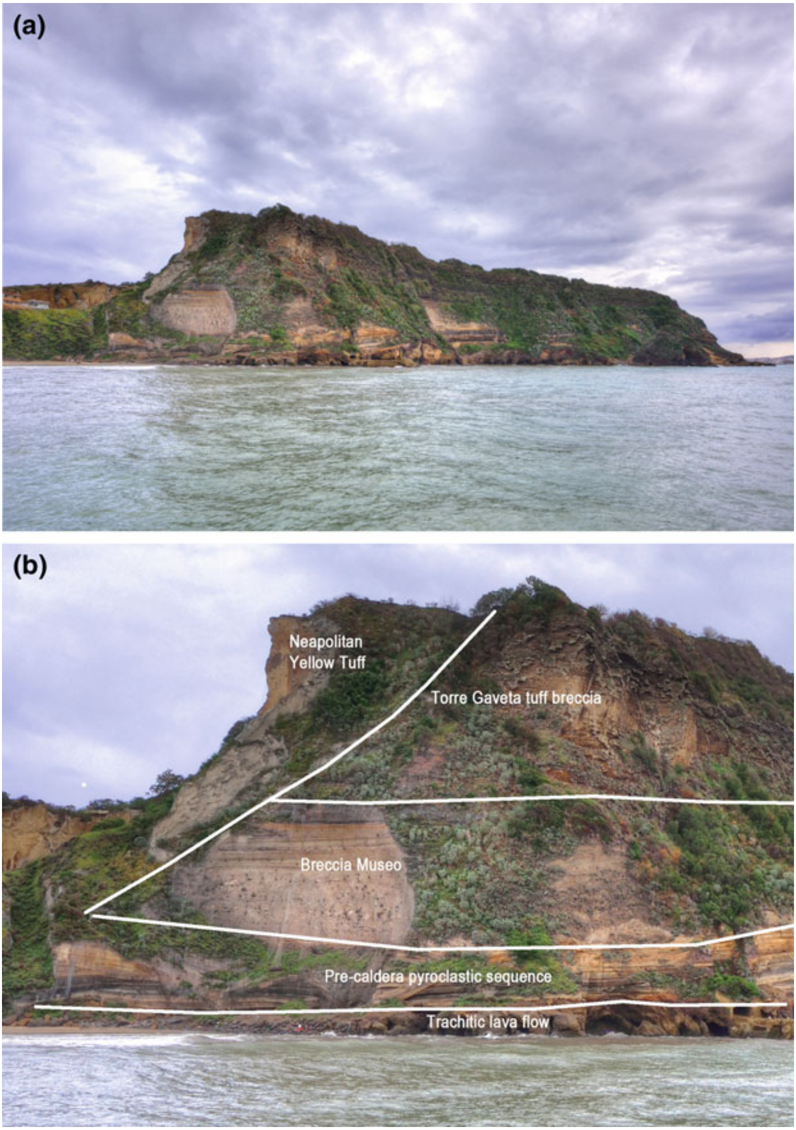
Fig. 2.22 Map of the Campi Flegrei with an indication of different volcanic units and the border of caldera collapses which occurred after the CI eruption 39,000 years ago and the NYT eruption 15,000 years ago (from Mayer et al., 2016). The extistence of caldera border associated to the CI eruption is still dabated

pyroclastic deposits were ejected during the two caldera-forming eruptions, while the majority of others eruptions produced less than 2.5 km^3 of pyroclastic deposits from monogenetic centres (Figs. 2.23, 2.24 and 2.25). Effusive eruptions sporadically created scattered lava domes.

The Campanian Ignimbrite eruption, the largest magnitude explosive event around the Mediterranean area over the past 200,000 years, strongly influenced the present geological setting and topography, producing a roughly circular collapse with a radius of 12 km (7.5 mi.). This eruption, together with the Neapolitan Yellow Tuff eruption, produced huge volcanic successions formed by ash, pumice and fragments from the deeper part of the volcano. This is the result of the spreading of pyroclastic flows and ash and pumice falls that occurred during the explosive phases, affecting an area of thousands of square kilometres. After the Neapolitan Yellow Tuff eruption, which produced a further collapse of the area at least 70 eruptions took place within the caldera, during three epochs of intense activity (15,000 ÷ 9,500;

Fig. 2.23 Particular of yellow tuff deposit (pyroclastic flow) with lithic and pumice (photo A. Fedele)

Fig. 2.24 A cliff of yellow tuff along the western boundary of the Campi Flegrei caldera (Torre Gaveta site) (photo A. Fedele)


(a)
(b)
Neapolitan
Yellow Tuff
Torre Gaveta tuff breccia
Breccia Museo
Pre-caldera pyroclastic sequence
Trachitic lava flow

◀ **Fig. 2.25** **a** Torre Gaveta marine cliff, located in the western sector of the caldera. Along this cliff it is possible to recognise a number of important volcanic deposits associated with the caldera activity. **b** At the base of the sequence, the older trachytic lavas outcrop and are overlain by the pyroclastic deposits of explosive eruptions which occurred before the caldera collapse. Above, the Breccia Museo is easily recognisable and represents one of the most debated volcanic formations of the Campi Flegrei volcanic district. The deposit, made up of six distinctive stratigraphic units, has been interpreted as the proximal facies of the major caldera-forming Campanian Ignimbrite eruption. Volcanologists use it to mark the boundary of the caldera. The Breccia Museo is partially covered by the breccia of Torre Gaveta volcanic centre. The Neapolitan Yellow Tuff overlies the whole of the above deposits, in unconformity. This tuff is associated with the eruption which produced a further collapse of the caldera (photo A. Fedele)

8,600 ÷ 8,200 and 4,800 ÷ 3,800 years ago) (Fig. 2.20). The last event occurred in 1538 A.D., after about 3,000 years of quiescence, and formed the Monte Nuovo tuff cone, west towards the town of Pozzuoli (Fig. 2.26). Volcanic activity in the Campi Flegrei was mainly characterized by phreatomagmatic eruptions, during which the magma rises into the crust and comes into contact with the water contained in the rocks, dramatically increasing its explosive energy. This activity is frequently accompanied by the formation of pyroclastic surges and abundant fragmented magma ejected into the atmosphere. Fallout deposits from the former epochs of volcanic activity were manly distributed towards the northeast sector of the caldera, up to about 15 km (10 mi.) from the caldera centre. Fallout beds are widely also

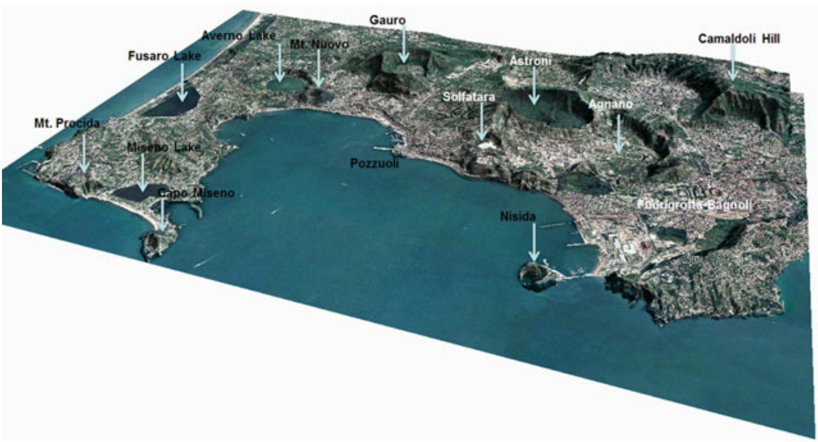


Fig. 2.26 The caldera of Campi Flegrei indicating the volcanic centres formed after the Neapolitan Yellow Tuff eruption (INGV-OV Archive)

distributed along the western margin of the Apennines, at a distance of about 50 km (30 mi) from the vent. Pyroclastic flows of the Campanian Ignimbrite eruption travelled within the caldera floor and reached the edges of the Campanian Plain. The eruptions which took place during the middle epoch were all low-magnitude events. The fallout deposits of the most recent epoch and of the Monte Nuovo eruption covered the caldera floor and its surroundings. The products of the Agnano-Monte Spina eruption, the largest post-caldera sub-Plinian event covered a large area as far away as the Apennines. Pyroclastic currents travelled across the caldera floor and secondarily over the northern slopes of the Camaldoli hill (Fig. 2.26 and 2.27). In the past 15,000 years, the caldera floor has been affected by tectonic resurgence, a phenomenon which is related to the pressure of magma at relatively shallow depth. This has resulted in a maximum net uplift of about 90 m (300 ft) at the La Starza marine terrace in the city of Pozzuoli. Ground movements have also been documented during the past 2,000 years and, in particular, since late 1960 s, episodes of unrest have been recorded by the *Osservatorio Vesuviano* monitoring systems, the largest ones taking place in 1969–1972 and 1982–1984 and generated uplifts of 170

Fig. 2.27 A view of the Phlegraean district from the Camaldoli Hill (see Fig. 2.26 for location), the dotted line representing the boundary of the caldera. The latter's collapse and the volcanic activity formed a complex landscape with hills, plains and cliffs that characterise the city of Naples (photo A. Fedele)

and 180 cm respectively, and the evacuation of part of the town of Pozzuoli (this topic will be widely debated in the last chapter). The geometry of these short-term deformation events is very similar to that of long-term deformations and most likely indicates a similar stress regime over at least the past 5,000 years. Seismicity has been documented in the Campi Flegrei caldera since the 15th century. Historical chronicles describe the many earthquakes felt by Naples' inhabitants in the 2 years preceding the last Monte Nuovo eruption. Moreover, seismic data recorded over the last 30 years has evidenced the occurrence of earthquake events connected to the uplift phases of unrest. In recent years many authors have invoked the role of geothermal fluids in both volcano seismicity and deformation. The most evident volcanic manifestations of the caldera are nowadays located a few kilometres northeast of Pozzuoli, inside and at the outer eastern border of the Solfatara crater, which was formed during the last period of eruptive activity, about 4,000 years ago (Figs. 2.28 and 2.29). The crater has many hot fumaroles and springs, with temperatures up to about 100 °C and emits a large amount of CO_2 (about 1,500 tonnes

Fig. 2.28 A view of the Solfatara crater from above. It is located in the central sector of the Campi Flegrei caldera, and is the area with the most vigorous fumaroles emissions. The crater is characterized by a sub-hexagonal shape and bounded by NW–SE, SW–NE, and N–S trending ring faults. This volcano was formed during the most recent epoch (epoch III) of volcanic activity at the Campi Flegrei, about 4,200 years ago (photo A. Fedele)

Fig. 2.29 The scaling of certain minerals (Sulphur, S and realgar or ruby sulphur, arsenic sulphide AsS) contained in the fumaroles of the Solfatara geothermal system, produces this typical reddish-yellow colour close to the vents. The presence of hydrogen sulphide (H_2S) also produces the characteristic smell of rotten eggs (photo A. Fedele)

per day). This is the most visited site in the caldera because of its spectacular evidence of the large heat flow released from the surface.

2.5 The Volcanic Island of Ischia

The two islands of volcanic origin, which border the Gulf of Naples to the west and fall within the Phlegraean volcanic district are those of Procida and Ischia. While volcanism on Procida is considered extinct, the island of Ischia is still active, as shown by many pieces of geological evidence including the volcanic-tectonic lifting of Monte Epomeo, which was active until about 5,000 years ago, the Arso eruption of 1302, the last on the island and the volcanic-tectonic earthquake of 1883 which caused more than 2300 victims, as well as the intense fumarole and hydrothermal activity that made the island one of the most famous places in the world for spa and thermal treatments. The island is about 18 nautical miles (33 kilometres) from Naples harbour and just over 6 (11 kilometres) from Cape

Miseno. Its morphology is dominated by the resurgent structure of Monte Epomeo (787 m/2484 ft.) (Figure 2.30), predominantly formed by the green tuff of the same name. In fact, while observing the morphology of the seabed, one can understand that the island of Ischia represents the emergent part of a much larger volcanic field, which develops predominantly in an east-west direction (Fig. 2.15).

The island covers 46 km^2 (18.6 sq. mi.) consisting of rocks that are derived from a number of explosive and effusive eruptions that date back about 150,000 years (Fig. 2.20). Beginning 55,000 years ago Ischia Island has undergone resurgence within a caldera that was formed after a large ignimbrite eruption (Monte Epomeo green tuff, 55,000 years ago). The total uplift deduced from the present height of the marine deposits and eustatic variations is 710 m (2330 ft.) in the southern sector and 920–970 m (3020–3180 ft.) in the northern sector, with uplift ranging from 23 to 33 mm a year. This rate of uplift is at least one order of magnitude larger than those observed in the tectonic uplift of mountain ranges. The uplift that involves the central part of the island is thought to be associated with the inputs of magma at shallow depths, which, between 28,000 and 18,000 years ago, produced eruptions and volcanic deposits of a significantly different composition to

Fig. 2.30 A view of the island of Ischia from the eastern side, during the approach of the ferryboat to the island. The main structural element of the island is the 787 m Monte Epomeo (visible on the right) (photo A. Fedele)

those of previous eruptions. The main area of activity involved in the resurgence is the block making up Monte Epomeo, which is located in Ischia's central sector, an area covering about 4×4 km^2. The edges of this block are marked by a system of subvertical faults with northwest–southeast, northeast–southwest and north–south strikes. Different models have been proposed for the resurgence of Monte Epomeo and the volcanic activity that is localized around the uplifted block, and most of these involve a shallow magma body that has produced uplift following the formation of the caldera. This idea was first proposed by Alfred Rittmann (1930) who spent a lot of time in the study of the dynamics and tectonics of the island. In the last phase of uplift, between 8,600 and 5,700 years ago, the summit of the Monte Epomeo was progressively dismantled by the occurrence of huge landslides (debris avalanches), as consequence of its relatively rapid uplifting and gravitational instability. This process is testified to by the horseshoe shape of the crest and by the large hummocky deposits off-shore to the south and west of Ischia. Huge block falls, carried during the avalanches, can be seen in different areas of the island, both on-shore and off-shore, such as along the beaches of San Francesco (Forio) and Lacco Ameno (the western part of the island) or in Serrara Fontana (in the south).

The phases of volcanic activity of the island of Ischia have been grouped into an older cycle and a younger cycle, the transition between which was marked by the great alkali-trachytic ignimbrite eruption of Monte Epomeo Green Tuff. Between 55,000 and 33,000 years ago explosive activity took place and the caldera depression, formed after the Monte Epomeo Green Tuff eruption, was filled both under sub-aerial and submarine conditions. The onset of the two main subsequent volcanic phases (the first between 29,000 and 18,000 years ago and the second 10,000 years ago through to 1302 A.D.) indicate the arrival of new magma from a deeper zone that was feeding the eruptions. These two phases were characterized by the occurrence of small to moderate explosive eruptions and lava flows. The last eruption in 1302 A.D. produced a lava flow in the eastern sector. At present, Ischia Island has a vigorous hydrothermal system, with a maximum surface temperature above 100 °C, while a general subsidence trend of the island has been observed since Roman times (2,000 years ago). This trend, is generally correlated to a low risk of eruptions.

2.6 The Urban Area of Naples: The City Between Two Volcanoes

The city of Naples rises between the two active volcanic areas of the Phlegraean district to the west and Mount Vesuvius to the east. The intense urbanisation of the city makes it difficult to read the geological landscape. It has undergone profound human transformations, due not only to the high level of construction but also because of the extensive quarrying activities for the extraction of yellow tuff as a building material. However, important geological and orographic elements can still be recognized, consisting of small hillocks and vertical tuff walls, the result of the volcanic activity of the Phlegraean district, and cuttings determined by the ancient watercourses that once crossed the current urban area. Several small eruptive monogenic centres have been identified in the city of Naples, some of which are of an age following the eruption of the Yellow Neapolitan Tuff. It is possible that the volcanic activity of these eruptive centres is related to the tectonic structures of collapse of the Campanian Ignimbrite and Neapolitan Yellow Tuff, along which the rise of the magma generated low energy and short duration volcanic activity. In this sense, the advent of volcanic activity in the city of Naples has to be correlated with the more eastern outliers of the Phlegraean volcanic district (Fig. 2.31).

The main orographic element of the city of Naples is the Camaldoli Hill (475 m/1558 ft asl), a structure that volcanologists associate with the formation of the caldera of the Campi Flegrei following the Campanian Ignimbrite eruption.

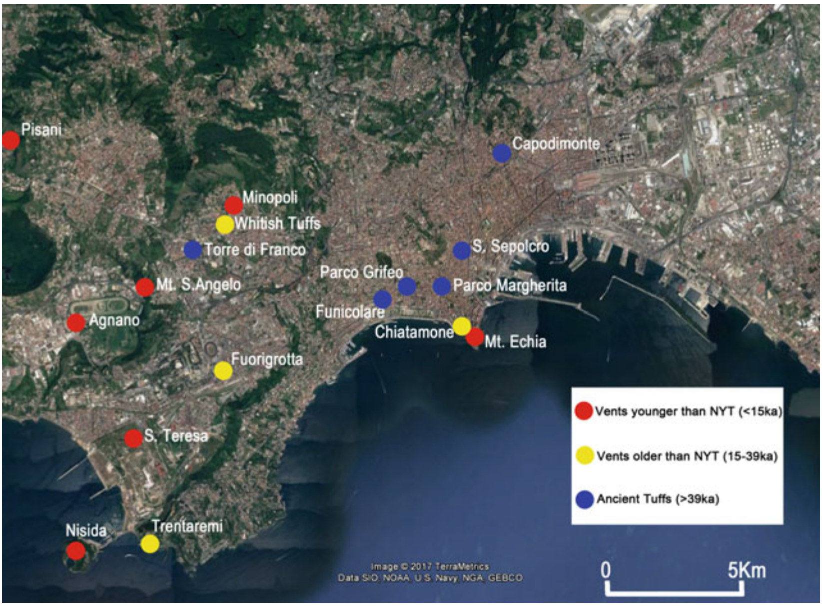


Fig. 2.31 The city of Naples with the location of the eruptive vents associated with different eruptive periods (after Scarpati et al., 2013)

This margin extends south and then southwest to the hill of Posillipo which certainly constitutes the most important part of the Naples landscape as well as hosting the city's most luxurious residential district. The Camaldoli Hill slopes gently towards the north and east, while it has vertical and sub-vertical walls on the southern slope, facing the Fuorigrotta-Bagnoli plain (Fig. 2.27). Along these cliffs one can note the presence of ancient tuffs in the lower part of the formation prior to the Campanian Ignimbrite eruption. Above these deposits, from the bottom up we encounter the Campanian ignimbrite (39,000 years), the pyroclastic products laid down between 39,000 and 15,000 years ago, the Yellow Neapolitan Tuff (15,000 years) and the volcanic deposits from the most recent activity (less than 15,000 years ago). These stratigraphic data suggest that the Camaldoli Hill is a relict of the ancient Phlegraean caldera. The hill of Posillipo, however, is an elongated south-facing formation which terminates in the islet of Gaiola and, not far to the north-west, the Trentaremi eruptive centre (around 20,000 years old), which forms a beautiful bay open to the south (Fig. 2.32). Further west one encounters the islet of Nisida, a volcanic structure formed around 4,000 years ago, the western side of which was partially demolished by wave action, creating a narrow passage within a circular basin known as Porto Paone. The most interesting

Fig. 2.32 The little bay of Trentaremi, east to Posillipo hill, is a relic of a volcanic centre formed between the Neapolitan Yellow Tuff (15,000 years ago) and the Campania Ignimbrite (39,000 years ago) (from Google Earth)

morphological and geological evidence regarding the hill of Posillipo is best observed from the sea. Along this coast the stratifications of the Neapolitan Yellow Tuff are very evident and the sea view offers a unique panorama of the city of Naples. At the westernmost point of the hill of Posillipo, one encounters the plain of Fuorigrotta-Bagnoli, the morphology of which is linked to volcanic-tectonic sinking events of the Phlegraean zone and the subsequent filling of the depression with the deposition of the eruptive products of the post-Yellow Tuff activity and sea sediments. That the ingression of the sea occurred followed the last glaciation between 20,000 and 10,000 years ago is evidenced by the presence of sandy deposits and marine fossils typical of shallow seas found in a deep perforation in the area of Bagnoli. In this area there is also the small crater of Santa Teresa, probably formed around 10,000 years ago, after the Yellow Neapolitan Tuff eruption.

Another predominant orographic element that dominates the city of Naples is the hill of Vomero (Fig. 2.27), the highest point of which lies in the tufaceous ridge of San Martino (249 m/817 ft), dominated by the Castel Sant'Elmo. From here you can enjoy one of the most beautiful and exciting panoramic views of Naples (Fig. 2.33). In this area one can identify volcanic products of various types including a small lava dome and some sequences of ancient tuffs close to the age of

Fig. 2.33 The astonishing view of the city of Naples from the San Martino hill. The Somma-Vesuvius volcanic complex in the background, dominates and characterizes the landscape (photo A. Fedele)

the Campanian Ignimbrite eruption. The southernmost slope of San Martino relief slopes away down towards the hill of Pizzofalcone, which ends with Monte Echia, where the earliest settlements of the pre-Christian era of Naples have been found. Pizzofalcone originally resembled a small peninsula surrounded by the sea, a morphology today masked by the subsequent infill of an anthropic nature, which has pushed out the coastline by several tens of metres. Monte Echia is also considered to be an eruptive centre, probably ancient, but still of uncertain age. To the north of the ancient centre of Naples there is another important landscape element, the hill of Capodimonte, the morphological remains of an ancient eruptive centre older than 39,000 years. This area is represented by a block that gently slopes to the north, while the southern limits are more broken up. This last morphological element is also to be attributed to intense quarrying activity when the tuff was extracted as a building material in the past. Proceeding eastwards, one passes on to a flat landscape, in the area that is the plain of the river Sebeto, on average just above sea level. The watercourse was progressively erased, first during the Bourbon era, with the excavation of canals to feed watermills, then with the exploitation of the wells in the area of the springs of Lufrano, and then, in the most recent period, buried by intense urbanisation and reduced to little more than a sewer.

The presence of marine-marsh and fluvial sediments, also found in various drillings, and volcanic deposits, of both in Phlegraean and Vesuvian activity, shows that this area has undergone a subsidence process and that the most sunken area was subsequently backfilled with terrestrial materials carried from areas in the hinterland and with pyroclastic materials from explosive volcanic activity. This area connects gently with the slopes of Vesuvius, whose eruptive activity, until 1944, strongly influenced the expansion of Naples to the east, which then increased radically following the volcano's quiescence.

2.7 The Most Dangerous Phenomena of Volcanic Eruptions

When the Roman city of Pompeii - buried by the ash and pumices of the 79 A.D. eruption of Vesuvius - was discovered in the 18th century, it was not immediately clear the phenomena that caused such damage and devastation. Later observations of explosive eruptions worldwide and the application of the physics of fluid dynamics to volcanic processes, showed that gravitational instability of large and hot ash clouds, produced during volcanic eruptions, can generate so-called pyroclastic flows (or pyroclastic density currents). It represents one of the main threats

Fig. 2.34 Pyroclastic flows down the flank of the Mayon volcano (Philippines), during the 2018 eruption (from asiage.com)

related to explosive eruptions. A pyroclastic flow is a fast-moving current composed of hot gases and tephra, which increases its speed and energy as it moves away from the volcano (Fig. 2.34). These flows can reach a velocity of up to 300 kph (185 mph) with a temperature ranging from 70 °C to 800 °C. The pyroclastic flow can be produced not only through the gravitational collapse of the eruptive columns but also by the failure and collapse of lava domes or by directional blast. In the latter case a part of volcano collapses producing a quick depressurisation of the magmatic system and transforming the explosion into a gravity-driven current (Fig. 2.35 and 2.36). The capacity for devastation of pyroclastic flows is related to their high dynamic pressure and temperature (Fig. 2.37), causing rapid death and serious damage to buildings and infrastructure. Diluted pyroclastic flows have a physics similar to those of base surges generated during nuclear explosion tests. The similarity was observed during nuclear tests and, later, in 1998, Greg Valentine studied the effects of pyroclastic flows and surges, inferred from the effects of nuclear weapons. He showed that the dynamic pressure is proportional to the flow density and to the square of velocity. Thus, the higher the flow density and the greater its velocity, the greater its potential for causing damage. Perhaps, the most famous (and infamous) pyroclastic flow occurred in 1902 on the French Caribbean island of Martinique and swept down the slopes of the Mount Pelée volcano, incinerating the small port city of Saint–

Fig. 2.35 The huge lateral blast that opened the 1980 eruption of Mt. Saint Helens (Washington, US). More than 50 people were killed directly, including the innkeeper Harry R. Truman, photographers Reid Blackburn and Robert Landsburg, and the volcanologist David A. Johnston. Hundreds of square kilometres of forest were reduced to wasteland, causing over a billion U.S. dollars in damage (photo Keith Ronnholm)

Pierre and killing 29,000 residents. After the eruption only one person survived on the island, and he was being held in the city prison.

The high concentration of ash in the lower atmosphere during explosive eruptions, can affect human health, producing serious breathing problems. Ash is also carried into the higher atmosphere by the eruptive column, and transported by the wind at distances of hundred to thousands of kilometres from the vent, reaching the altitudes used by aircraft *en route*. This fine and high concentration of silica ash particles in the air represents a serious threat to aeroplane turbines. A case study is the 2010 eruption of Eyjafjallajökull in Iceland. In mid-April of that year, as the ash cloud spread eastwards towards Europe, a large section of European airspace was closed down, with more than 100,000 flights cancelled over 8 days. Medium to heavy damage was also recorded to roads and services due to the high levels of accumulating ash (Fig. 2.38).

Fig. 2.36 The shape of Mt. Saint Helens before and after the 1980 eruption. The northern flank of the volcano was completely swept away, after the eruption, and leaving a new crater within which volcanic activity continued (from wordpress.com)

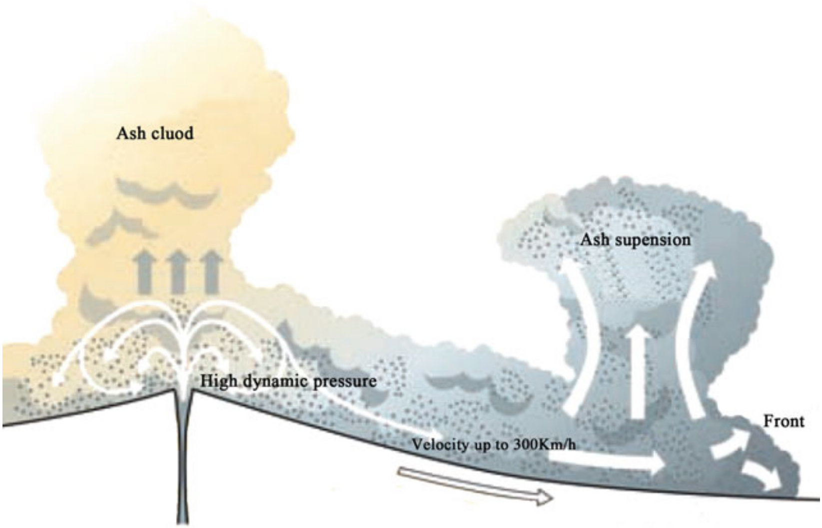


Fig. 2.37 A sketch of a pyroclastic flow. This is formed by a zone of high dynamic pressure, where a mixture of hot gases, ash, pumice and parts of the volcano edifice are carried at velocities of hundreds of kilometres per hour. During this movement, as the energy decreases, the flow deposits the volcanic material progressively (the heaviest first followed by successively lighter components). Air is incorporated at the front of the flow and heated, producing the expansion of the flow, while the buoyancy effect of the less dense mixture generates an ash suspension (after Carlino and Luongo, 2005)

A further, and not negligible problem related to explosive eruptions, is in fact the fall of ash and pumices produced during Plinian-like activity. When the effect of gravity becomes dominant on the buoyancy and wind forces, the particles of ash and pumice injected into the atmosphere fall and are deposited on the ground in varying thicknesses. Just a few tens of centimetres (12–24in.) of ash accumulation represents a threat to the stability to the roofs of buildings and for many other activities such as transportation, industry and services. The accumulation of large volumes of tephra around the volcano is an additional threat, because these ash and pumice accumulations are unstable and can be easily remobilized by the rains or by the melting of ice in volcanoes at higher latitudes or altitudes, generating the so called “lahars”, a type of mudslide with large destructive potential. The risk related to such phenomena is further increased by the injection of fine particles of ash into the atmosphere which act as nuclei for the condensation of water, enhancing the

Fig. 2.38 The eruptions of Eyjafjallajökull in Iceland, occurred in 2010. Although it was a relatively small in terms of energy, the event caused enormous disruption to air travel across western and northern Europe over an initial period of six days in April 2010 which continued intermittently into May of the same year (from diegoarcos.com.ec)

likelihood of rainfall during and after an eruption. An infamous example of serious damage due to a lahar event is that of the 1985 eruption of Nevado del Ruiz (Colombia, South America) in which more than 23,000 persons were killed. It was a relative small eruption (VEI = 3), but ice and snow covering the summit were melted by the eruption generating lethal lahars, which destroyed the city of Armero located at a distance of about 50 km from the volcanic peak.

Volcanoes are sometimes silent but, in many cases, continue to degas because the cooling of magma stored in the crust produces a large amount of sulphur and carbon dioxide that migrate upwards towards the rock fractures. These gases can accumulate at the surface and represent a potential risk for human health. For instance, a CO_2 concentration in the air above 7% produces serious breathing problems, while there is a risk of death for concentrations above 25%. There have been a few cases of death due to gas emissions from active volcanoes, such as Dieng Plateau (Java) in 1978, Lake Monoun (Cameroon) in 1984 and Lake Nios (Cameroon) in 1986.

Active volcanoes continually change their shape because of the alternation of explosive and effusive eruptions produces, respectively, the dismantling and the growth of volcanic structure. Many volcanoes have a perfect cone-shape such as the Fujiyama in Japan, which is an icon for volcanologists, despite its shape being destined to change if there is a large explosive eruption. In fact, the profile of a volcano is the result of a hydrostatic equilibrium, which depends on the density of the pyroclastic material and lavas and the ratio between the width and the height of the edifice. A disequilibrium of the hydrostatic surface, for instance due to excessive volcanic growth, generates a gravitational instability of the slope. In this case, earthquakes and volcanic deformations accompanying the magma uprising can trigger or enhance the failure of entire sectors of the volcano, generating huge debris avalanches. This represents a truly unpredictable and dangerous phenomenon. Worldwide, many volcanoes have a peculiar horseshoe-shape, which is the result of flank failure and avalanches occurring during explosive eruptions, testifying to the large gravitational instability affecting these mountains. A well-known case study is the cataclysmic eruption of (Washington State, USA) which occurred in 1980. By May 18th of that year a bulge of viscous lava, formerly intruded into the flank of Mount St. Helens, reached a point of great instability and began creeping rapidly towards failure. Soon after, a magnitude 5 earthquake shook the volcano and triggered a huge debris avalanche, which in turn unloaded the confined pressure at the top of volcano, producing a giant lateral blast. The immense explosion and the avalanche completely devastated a radius of nearly 30 km (18 mi) westwards and more than 20 km (12.4mi) northward from the summit (Figs. 2.35 and 2.36). Fortunately, this area was quite uninhabited and mainly covered by forests. The scientists had not predicted the behaviour of this volcano. In fact, the volcanologist David Johnston, a scientist of the monitoring team, died while manning an observation post 10 km (6 mi) from the volcano summit, a distance that he supposed was safe. His last words, before he was swept away by the lateral blast, were "Vancouver! Vancouver! This is it!"

A horseshoe shape can be also observed on the Monte Somma-Vesuvius volcano complex. Monte Somma is, in fact, the older remains of the volcano, affected by explosive eruptions and large avalanches involving its southern sector and leaving a small apical caldera. The new space inside Monte Somma has been progressively filled by subsequent eruptions, forming the present structure of the Vesuvius crater.

The unpredictability and randomness of the volcanic phenomena described, such as pyroclastic flows or debris avalanches, highlight the chaotic nature of physical processes governing volcanic eruptions. The monitoring and the study of volcanoes are thus crucial to anticipating the alerts for the evacuation of people at risk as early as possible.

2.8 The Largest Eruptions of the Neapolitan Volcanoes

Current knowledge of the great explosive eruptions on Earth is limited and despite having a potentially devastating large-scale impact, only a few of them have been studied in detail. The frequency of high-energy eruptive events (VEI > 4) is very low and this limits the possibility of studying the mechanisms of major explosive eruptions, such as those that generate the calderas. These eruptions are typically associated with the emission of great volumes of ash and pumice, forming massive layers of pyroclastic material that cloak the topography. These deposits are called "ignimbrites" which is the name given to "ignimbrite eruptions" which are characterised by pumice-dominated pyroclastic flow deposits with subordinate ash and lithics. These large deposits can cover thousands of square kilometres and often appear as coherent, well-compacted, often partially welded layers that in some cases resemble lava flows. At least seven large-explosive eruptions can be recognized in the Neapolitan area (Fig. 2.39), some of which, such as those of the Campanian Ignimbrite eruption of 39,000 years ago in the Campi Flegrei or the Avellino eruption (3,800 years ago) and Pompeii (79 A.D.) generated by Vesuvius, have been extensively studied by volcanologists.

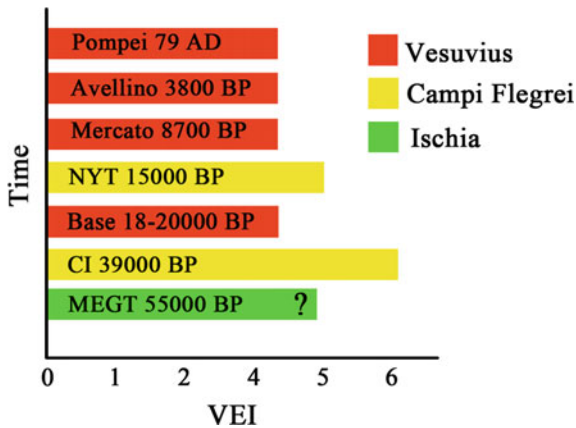


Fig. 2.39 The major explosive eruptions (VEI > 4) identified in the Neapolitan volcanic district (Vesuvius, Campi Flegrei and Ischia). The VEI of the MEGT eruption is very uncertain (NYT: Neapolitan Yellow Tuff; CI: Campania Ignimbrite; MEGT: Monte Epomeo Green Tuff)

2.8.1 The Mt. Epomeo Green Tuff Eruption, Ischia Island

Although this is one of the least famous and least quoted, it is, as far as we know, the oldest high energy eruption among the Neapolitan volcanoes is that of the Green Tuff of Monte Epomeo on the island of Ischia, which took place some 55,000 years ago. The volcanic history of the island of Ischia is more ancient, dating back at least 150,000 years ago, and was influenced by volcanic-tectonic processes linked to the particular magmatic feed system and periodic eustatic changes in sea level, with an important interaction between sedimentation processes and volcanism. The explosive eruption of the Monte Epomeo Green Tuff was fuelled by a trachytic magma whose rapid emission would have led to the collapse of the central part of the island and the formation of a caldera whose structural limits are only partially recognizable in the south-east and north-west sectors. The size of the caldera is approximately 10 × 7 km (6 × 4 mi), with the largest axis oriented east-west, while the average collapse (vertical down drop) is of the order of 300 m (1000 ft). Based on these data, it can be assumed that the volume of magma emitted to generate such a sinking is of the order of several tens of cubic kilometres. Nevertheless, both the moderate scale of the dispersion of the products of this eruption and the scarcity of tephras in areas facing the island suggest that the magma volume emitted during the eruption itself may be lower. It is possible, however, that the lack of stratigraphic evidence of this great eruption beyond the island is also determined by the absence of specific studies aimed at the identification and dating of the Monte Epomeo Green Tuff deposits and the difficulty of obtaining deep stratigraphy on the seabed. Following this eruption and after the caldera's subsidence, a part of the central sector of the island was invaded by the sea, while eruption products filled the depression forming a massive pyroclastic deposit, known precisely as Monte Epomeo Green Tuff (Figs. 2.40 and 2.41). The greenish colour that characterizes the tuff of Ischia is due to phenomena of marine and hydrothermal alteration that have sometimes also resulted in poor compaction of the deposit. The Green Tuff outcrops along most of the north-eastern slope of Monte Epomeo. This mountain, which dominates the island landscape, is a volcanic-tectonic structure, uplifted by the push of shallow magma, following the eruption of 55,000 years ago. The uplifting of Monte Epomeo in the last 33,000 years is evidenced by the presence of marine fossils found at altitude and was studied in detail by Rittmann in 1930 who deduced that it is the result of a volcanic-tectonic process that was active up to at least about 5,000 years ago.

Fig. 2.40 The Monte Epomeo Green Tuff outcrops widely along the Island of Ischia and is often used to build houses and churches. This is the example of the San Ciro Church, in the Serrara Fontana municipality, which is made of blocks of green tuff (photo A. Fedele)

Fig. 2.41 The western flank of Monte Epomeo, formed of Green Tuff. It is characterised by severe gravitational instability that has produced numerous landslides during the resurgence process (photo A. Fedele)

2.8.2 The Campi Flgerei Caldera-Forming Eruptions

The largest eruptive event in the Neapolitan area, one of the largest recorded on the European continent and certainly among the most studied, is attributed to the Campi Flegrei. About 39,000 years ago, the current area of the Campi Flegrei was the scene of a giant volcanic eruption that caused the collapse of an almost circular area. This has a diameter of about 12 km (7.5 miles) with a centre in the town of Pozzuoli (west of Naples), and forms a large caldera, whose structural limits are the promontory of Monte Procida to the west and in the hill of Posillipo to the east. The eruption was fuelled by at least 150 km^3 of trachytic magma but the manner in which it took place is not yet clear to volcanologists, so that the mechanism of eruption is still subject to debate. The eruption, known as the Campanian Ignimbrite, probably begins with a Plinian phase, with the formation of a tall eruption column at least 40 km (25 mi) high. The interaction of magma with the water contained in the rocks during its ascent resulted in a strong increase in explosiveness and the eruption became more turbulent with the formation of giant pyroclastic flows. It would seem that these high temperature flows (over 500 °C were been able to travel more than 80 km (50 mi) from the eruptive centre, spreading out over an area of about 30,000 km^2 (12,000 mi^2) and overcoming morphological features up to about 800 m (2600 ft) high (Fig. 2.42). The emptying of the magmatic chamber, following the release of large amounts of magma, caused the crust to sink and the formation of the caldera (Fig. 2.43a, b). However, many questions still remain about the deposition mechanism of the erupted material. The first doubt arises from the large area covered by the pyroclastic flows (Fig. 2.44), which, according to some scholars, cannot be related to a single eruptive centre located in the caldera of the Campi Flegrei. The first to provide an interpretation on this aspect was Breislak in 1798, who considered the deposition of the Campanian Ignimbrite as the product of an eruption by several emission centres across the Plain of Campania. Subsequently, a similar hypothesis was taken up by other researchers, according to whom the eruption would have taken place from a series of regional fractures nearby, to the north of the Campi Flegrei. The hypothesis of a single eruptive centre within the current caldera was initially proposed by Alfred Rittmann in 1950. According to the Swiss geologist, the Campanian Ignimbrite eruption caused the decapitation of an old volcanic layer termed the "*Archiflegreo*" (or "ancient Phlegraean"), although subsequent

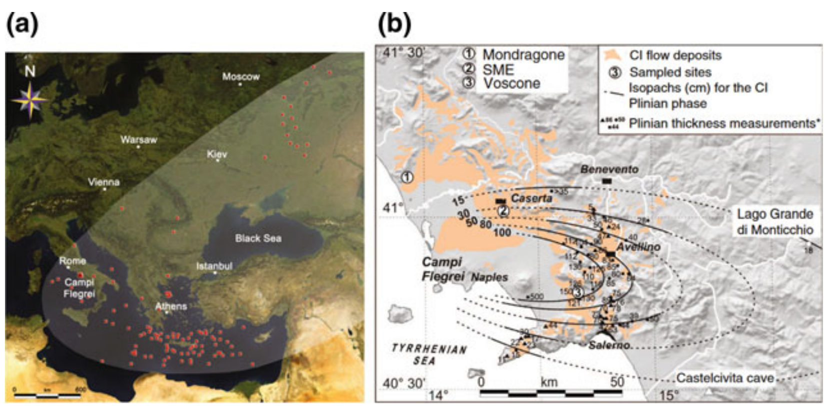
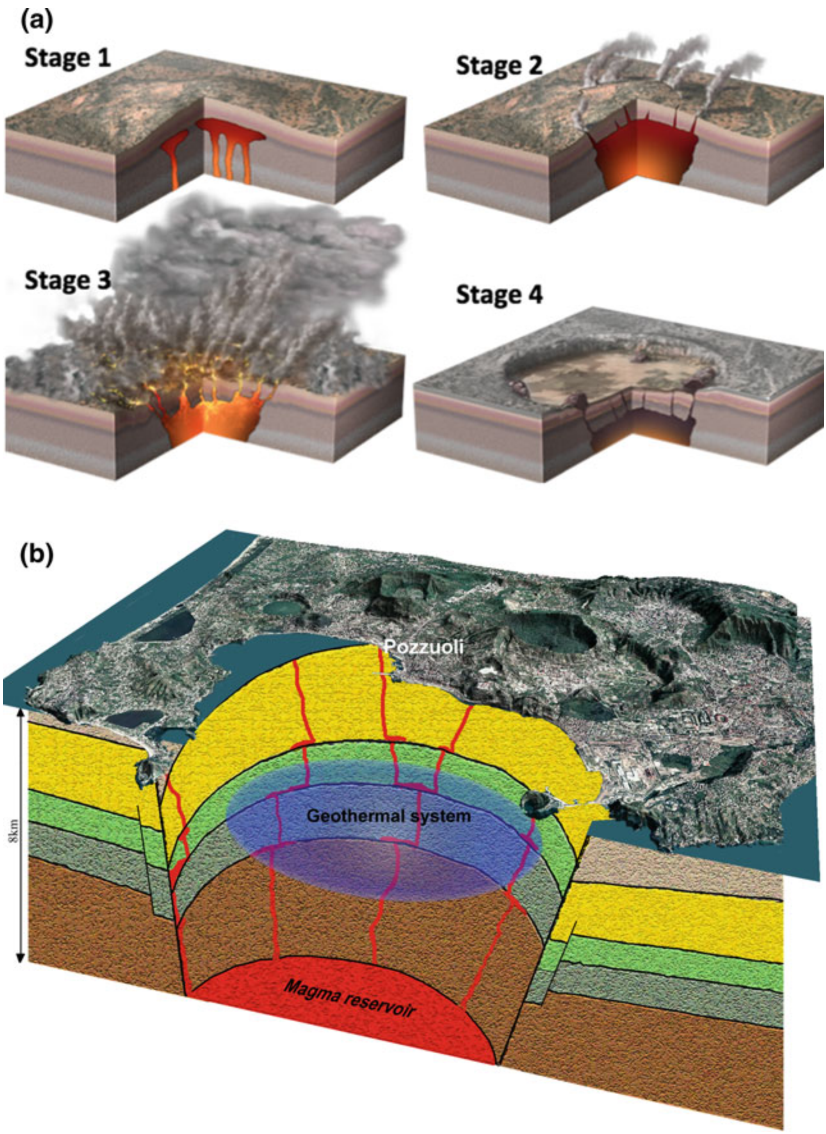


Fig. 2.42 **a** General dispersion of Campania Ignimbrite tephra and location of the sites where the volcanic deposits have been found (red boxes). **b** Isopach map of the Plinian fall deposits (in cm) and locations where the flow units are exposed. The pyroclastic flow deposits of this eruption flooded the entire Campania Plain and rose across the Apennines to an altitude of several hundred metres above sea level (after Smith et al., 2016)


(a)
Stage 1
Stage 2
Stage 3
Stage 4
(b)
Pozzuoli
Geothermal system
8km
Magma reservoir

◀ **Fig. 2.43** **a** The general mechanism of a caldera-forming eruption. In the stage 1 and 2 a large amount of magma is injected into the shallow crust producing a doming above the magma chamber. The crust is thus stressed to exceed the rupture limit when a viscous and gas-enriched magma emerges at the surface, producing a large eruption (3). The depressurization of the chamber, due to magma drainage, generates a catastrophic collapse, forming a caldera (4). Otherwise, the mechanism of large caldera formation is still debated and other hypotheses to explain their genesis have been proposed since the first studies of Smith and Bailey (1969); **b** a sketch of the possible deep configuration of the Campi Flegrei caldera magmatic system. A deep, partially cooled magma reservoir (with high crystal content) is located at a depth of about 8 km, feeding the eruptions that brought about the caldera collapse (Campania Ignimbrite, 39,000 years ago and Neapolitan Yellow Tuff 15,000 years ago). The magma migrated upwards after the Neapolitan Yellow Tuff event, forming limited batches and feeding the smaller eruptions of the most recent epoch. A high temperature geothermal system is develops at depths of between 0.5 and 3 km (© stefano.carlino@ingv.it)

stratigraphic studies did not reveal any geological evidence of the existence of such a volcanic edifice. Many authors later confirmed the hypothesis of the eruptive centre confined within the Phlegraean caldera of or its edges, but no reliable geological evidence has been found to definitively refute one hypothesis rather than another.

The Campanian Ignimbrite eruption released into the atmosphere a large amount of volcanic ash, which, thrust into stratospheric currents, deposited on an area of between 2 and 4 million km^2 (800,000–2.6 million mi^2) across the Eastern Mediterranean, Greece, Bulgaria, the Black Sea and Russia. Precisely because of the vast area it covered, once dated using radiometric methods, this layer of ash, known as the "Y5 layer", has been used as a reference for archaeological and palaeo-environmental dating. Some studies carried out by researchers at the University of Naples and the Laboratory of Prehistory in St. Petersburg attribute a major impact of the Campanian Ignimbrite eruption on humankind, involving the entire European continent.

The eruption occurred during a period (about 40,000 years ago) in which the Europe was involved in a measureable climate disturbance (the so called Heinrich Event 4) and human migration. The injection of a million cubic kilometres of ash and sulphur into the atmosphere due the eruption, possibly contributed to alter climate as well as provoking ecological disturbance within Europe. The combined impact of ash fallout and abrupt climatic deterioration possibly destroyed the ecological niches of the Neanderthals, contributing to their extinction. However, the above hypothesis and arguments cannot be confirmed because of the complexity of the natural system and the lack of sufficient scientific data.

Fig. 2.44 **a** Deposits from the pyroclastic flows of the eruption of the Campania Ignimbrite, along the coast of Sorrento (arrows) and **b** from the beach of Meta di Sorrento. If we consider the emission centre in the Phlegraean caldera, these flows would have travelled for over 30 km, largely across the surface of the sea. Some authors think that the eruptive centre of the eruption of the Ignimbrite Campana is not located within the caldera but along fractures located at its edges (photo A. Fedele)

The Campi Flegrei were the source of another great eruption, that of the Yellow Neapolitan Tuff, which took place some 15,000 years ago. The eruption probably had similar characteristics to that of the Campanian Ignimbrite eruption albeit with lower energy, as the erupted magma volumes are less, about 40 km^3. The eruption would have caused a new caldera collapse, located in the central area of the Phlegraean volcano, while eruptive products spread across a moderately large area, which includes much of the current city of Naples. The Neapolitan Yellow Tuff is, in fact, widely spread across the city's urban area, while to the west of the city this rock formation is represented only by limited outcrops. The structure of the caldera of the Campi Flegrei, generated following the Campanian Ignimbrite and Yellow Neapolitan Tuff eruptions has been studied not only through the outcrops of deposits and geological structures on the surface, but also through geophysical surveys and drillings that have reached a depth of 3 km (2 mi). The recording of micro-variations in gravity using very sensitive instruments (gravimeters), is of great help in studying volcanic and buried tectonic structures. During calderic eruptions, pyroclastic products (tephra) are produced in large quantities and these are characterized by their low density. The depressions left by the caldera eruptions are filled with these products, which, due to their lower density compared to the surrounding rocks, result locally in a negative variation in the gravimetric field (Bouguer's anomaly). The gravimetric measurements in the Campi Flegrei show a negative sub-circular anomaly with a radius of about 4 km, centred in the Gulf of Pozzuoli, just south of the city itself (Fig. 2.45). This area corresponds to the zone filled with tephra and to the main buried structure of the caldera's subsidence. However, a contribution to the negative variations in microgravity may also come from the lower density of deep rocks at high temperatures (at equal conditions, the density of a medium decreases as the temperature rises).

The drilling work carried out in the Campi Flegrei Deep Drilling Project (CFDDP), completed in 2012 in the eastern part of the area showed that the eastern part of the caldera was probably affected by a lesser volcanic-tectonic collapse than that observed previously. The volcanic products of the Campanian Ignimbrite and Neapolitan Yellow Tuff eruptions, dated using radiometric methods, were found in the CFDDP well at depths of about 450 m (1475 ft) and 200 m (650 ft) respectively, whereas these products appear to be at greater depths, probably more than a kilometre down in the western sector of the caldera. In the latter case, however, the absence of absolute radiometric dating on drilling cores picked up in the AGIP (gas and oil company) wells does not allow for reliable data on the deepest zone of the Phlegraean caldera.

There are still many open questions surrounding the dynamics of the caldera of the Campi Flegrei, especially with regard to the great eruptions which took place in

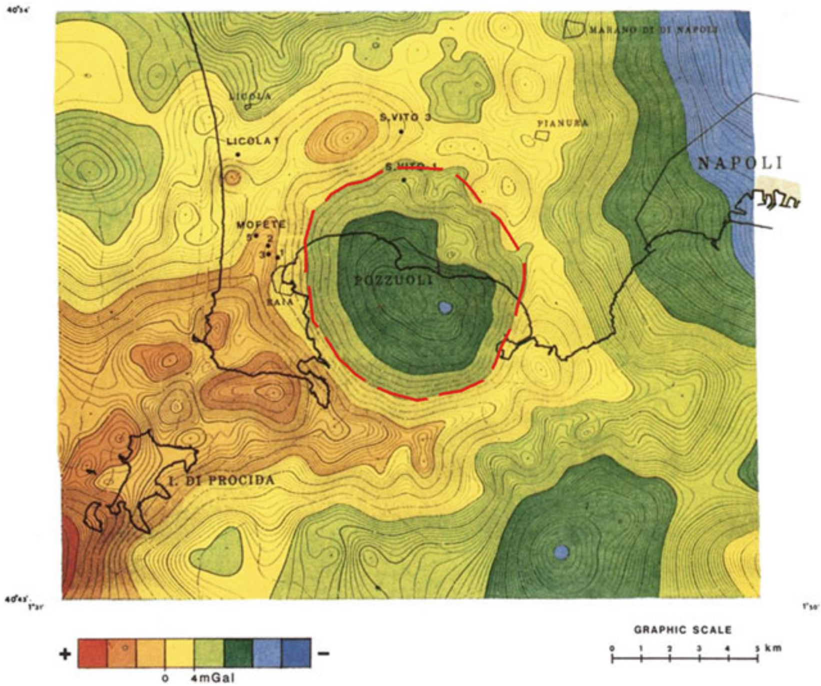


Fig. 2.45 The Bouguer anomaly map (density 2.4 g/cm^3; contour interval 0.25 mGal) of the Campi Flegrei caldera (after Barberi et al., 1991). The circular relative minimum in the centre of the Campi Flegrei is interpreted as the collapsed area of Neapolitan Yellow Tuff eruption filled by less dense deposits producing the observed anomaly. A contribution to this anomaly could be also provided by the high geothermal gradient which determines the lowering in density at a depth of a few kilometres

the past. There are no human testimonies of the eruptions such as that of the Campanian Ignimbrite, so we do not know how the Earth's crust may have behaved before these events, except through computer modelling. It is therefore essential to undertake further studies and deepen our geological knowledge of the area in order to provide more reliable answers on the precursors that appear ahead of a great ignimbrite eruption and the propagation mechanisms of the pyroclastic flows associated with these catastrophic events.

2.8.3 The Bronze Age and the 79 A.D. Vesuvius Eruptions

In the collective imagination the biggest eruption of Vesuvius is that of 79 A.D. which devastated Pompeii located 8 km (5mi) south of the volcano. Vesuvius however, caused damage at far greater distances during the Avellino eruption, which occurred in the Bronze Age, about 3,800 years ago. The name comes from the fact that pyroclastic deposits of this eruption were first discovered near the city of Avellino 60 km (37mi) east of Naples. This eruption was characterized by its high magma discharge rate, based on stratigraphic studies of eruptive products, of about 10,000 tonnes per second. The gravitational collapse of the dense eruptive clouds generated the formation of powerful pyroclastic flows that spilled over the volcano's slopes, especially in the north, at maximum speeds of about 150 metres per second (540 kph/330mph). These velocities have been calculated using numerical models based on observing the dispersion of the denser products within the pyroclastic deposit. In particular, the velocity of the pyroclastic flow is established on the basis of the minimum speed at which a particle of a given weight and density may remain suspended within the pyroclastic cloud. The observation of depositional structures is also helpful to volcanologists to estimate the flow energy and hence its possible range of velocities. The temperatures of the pyroclastic flows of the Avellino eruption were estimated at several hundred degrees Celsius. In the first 10–15 km (6–10mi) from the volcano, the energy of the streams and their destructive potential slowly dissipated gravitationally, depositing much of the heavier pyroclastic material (Fig. 2.46). However, the lighter part of the flow continued to travel to a distance of about 25 km from the volcano, hitting some Bronze Age villages, located northeast of Vesuvius, near the current town of Nola. Following the eruption, ash deposits covered a large part of the Vesuvian area, about 15 m thick in the vicinity of the volcano, and some tens of centimetres on the plains bordering the north, northeast and east of the volcano itself. Important archaeological finds of the Neolithic age have been brought to light in relatively recent times, showing the effects of this eruption at distances up to of about 15 km (10mi) from the eruption. Near the town of Nola archaeologists have discovered the remains of an ancient village with skeletons of buried animals and numerous human footprints left on the eruption deposits. About a kilometre east of the village, in San Paolo Belsito, human skeletons found in surge deposits showed that some people did not have time to get away before the arrival of pyroclastic flows. In other, neighbouring sites no human skeletons were found, probably because much of the population had fled previously, terrified by Vesuvius's eruption. This hypothesis has been supported by the finding of many human footprints in eruptive deposits, indicating the displacement of the population from around the volcano,

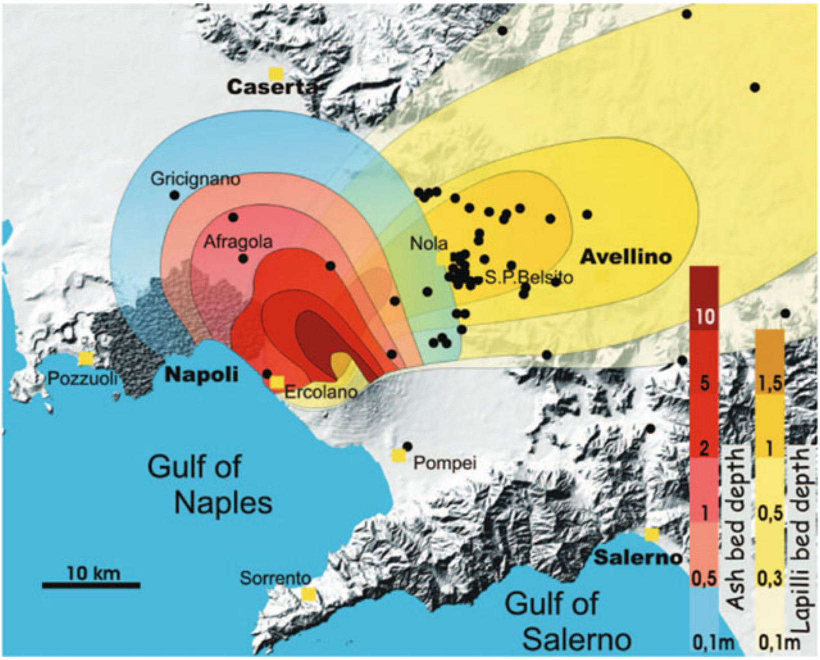


Fig. 2.46 The area covered by Avellino pyroclastic surge and fall deposits in the southeastern Campanian plain and surrounding uplands. Black dots represent the Old Bronze Age archaeological sites buried by the products of the Avellino eruption. Fallout lapilli and ash were deposited east-by-northeast of the volcano, whereas the surge clouds flowed down the volcano slopes in a generally NNW direction. Most sites within the fallout area (the yellow zone) were buried by a pumice and lapilli blanket thicker than 30 cm, which is above the limit for roof collapse. Structures in the surge area closer than 12 km from the volcano (the dark red zone) may have been swept away by the force of the cloud impact, whereas those at a greater distance would suffer less impact damage but still be affected by decimetres (the light red zone) to centimetres of fine ash bed or floods (the blue zone). The eruption affected a part of the present metropolitan area of Naples (bar scale values are in metres) (after Mastrolorenzo et al., 2006)

probably when the eruption entered a paroxysmal phase (Figs. 2.47a, b, c). The area north of Vesuvius was simultaneously affected by mud floods, a phenomenon that often occurs as a result of explosive, high energy eruptions, when deposited ash is displaced by heavy rains and carried by gravity towards downstream areas. At the time of the Avellino eruption during the Bronze Age, the area of Campania involved in the event was probably inhabited by a few thousand people who

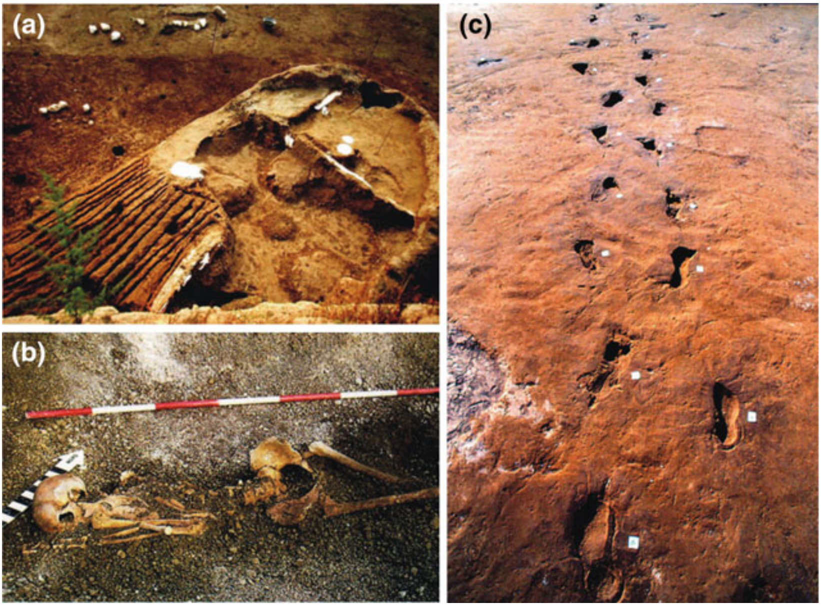


Fig. 2.47 **a** Archaeological evidence of the Avellino eruption. **b** The Bronze Age village of Nola. A group of huts, found 15 km northeast of Vesuvius, sealed by about 20 cm of surge and 20–40 cm of flood deposit. The hut roofs had partially collapsed, but interiors were filled by surge ash and well preserved; **b** a human victim of the Avellino eruption found at San Paolo Belsito, near Nola. The victim, a young woman buried by 1 m of pumice and lapilli, was found in a self-protecting position typical of death by suffocation; **c** footprints in the surge ash deposit of the Avellino eruption, found 15 km NNW of Vesuvius are possibly indicative of the escape of people from the village (after Mastrolorenzo et al., 2006)

abandoned the most badly affected area for many years. Some archaeological evidence shows that small post-eruptive settlements were established near Nola, but they were short-lived. There is in fact no evidence of new villages until at least 200 years after the eruption. The very low population density of the time instead allowed people to choose more secure settlements outside the area affected by the eruption, which for many years remained almost deserted. As a result of its effects and in particular the extent and distance from the volcano of the damaged areas, the Avellino eruption of 3,800 years ago can be considered to be one of the most powerful Vesuvian eruptions in the past and the only one, as far as we are aware, which had significant effects to the north of the volcano itself. The explosive eruptions of Vesuvius, in fact, usually affect the area to south, including the current cities of Portici, Herculaneum, Torre del Greco, Pompei and Torre Annunziata. The morphological configuration of Mount Vesuvius is open to the south, with the presence of the remnants of the ancient caldera of Monte Somma, which, however, closes off the structure of the volcano to the north and represents a degree of orographic protection for the towns to the north of Somma Vesuviana including Ottaviano and San Giuseppe Vesuviano. However, we do not know the exact morphology of the volcano before the Avellino eruption, which was most likely different from the present one. As will be seen later, such a breakdown, although having a relatively low chance of occurrence, would also pose potential risks to the central and eastern part of Naples.

Let us now come to the "Queen of Eruptions" for which it is worth expending a few extra words. There is no doubt, in fact, that the Pompeii eruption of 79 A.D. has always been of global importance in the study of eruptive phenomena and their effects on people and buildings. Underlying this notoriety there are two fundamental events: the discovery of the transcripts of the letters Pliny the Younger sent to his friend Tacitus, describing the salient moments of the eruption, and the uncovering of the cities of Pompeii and Herculaneum, starting from 18th century. These two events allowed volcanologists to date the eruption, reconstruct its main phases, and estimate their energy. It was August 24th 79 A.D. (although, as we shall see later, this date is being challenged by new studies) and roughly one o'clock in the afternoon when a cloud was noted rising from a mountain in the direction of the sunrise. This cloud, which "*by its size and shape*" had never been observed before, was followed by Pliny the Elder, Commander of the Miseno fleet, and his grandson, Pliny the Younger, who were both in Miseno, in the Campi Flegrei. It was then realized that that cloud was rising from Vesuvius. The volcano erupted unexpectedly for the Romans, although the signs that something was going on inside it had been frequent and sometimes intense. In fact, the area had been affected by earthquakes in the years prior to the eruption and, in the cities at the foot of the volcano one felt vibrations that sometimes left their mark on the buildings with cracks and collapses. But this activity did not provoke any serious alarm in the population, as Pliny tells us, because the Campanians were accustomed to earthquakes because of their frequent occurrence. Only the earthquake of 62 A.D. provoked panic in Pompeii, Herculaneum and Nocera, because the damage was severe and widespread. The great philosopher and writer Seneca himself witnessed the state of mind of the people affected by the earthquake with his work "*De terrae motu*". In fact the seismicity experienced by the Vesuvian population for some time before the 79 A.D. eruption would be interpreted, 19 centuries later, as the fracturing of the rocks pushed by the magma rising to the surface. Such earthquakes would be classified as precursors of an eruption.

But let us return to August 24th 79 A.D. The eruption initially produced an intense grey cloud that became increasingly tenuous as it rose. The cloud contained gas and solid material. The latter was made up of rocks torn from the volcanic duct, following an erosion process that accompanied the violent spurt of magma, together with pumice and ash that represented the different levels of fragmentation of a gas-rich magma. In the first phase of the eruption, the pumice and ash were pushed upward, forming a characteristic "pine-shaped" cloud, as described in the letters of Pliny the Younger. At that time the Romans were going about their daily tasks and no one immediately realized the real danger that hung over them. The cloud first lifted vertically over the eruptive vent and then bent to the southeast in the direction of Pompeii. The eruptive column soon reached an altitude of about 30 km (20 mi) before dropping pumice and ash throughout the southern sector of the volcano like heavy rain. The situation suddenly worsened, the air becoming so laden with ash as to make breathing difficult while in Pompeii the pumice began to accumulate in the streets, making the circulation of people and wagons difficult while the roofs that were now burdened by it began to collapse. Many inhabitants hid from the ash and lapilli (falling tephra) in their houses and, in part, moved away from the cities. Meanwhile, the Admiral of the Roman naval fleet, Pliny the Elder, received a message from Rectina (his friend and the wife of Tascus) who was in Pompeii. The Admiral departed with his quadrireme ships in order to help the people in danger but was forced to take refuge in Stabia, where he died, choked by the ash of the volcano.

Meanwhile, the first layer of light-coloured pumice (known as white pumice) had reached a thickness of about a metre (about 40 in.) in Pompeii, the Plinian cloud reaching a height of over 30 km (20 mi). The erupted magma changed composition, producing darker pumice (termed grey pumice) and was deposited above the white pumice to such an extent that the roofs of many houses began to collapse. In Pompeii itself the ground level was raised by about two and a half metres (8 ft).

The first phase of the eruption, according to the description contained in the letters of Pliny the Younger, lasted several hours, and certainly lasted until late in the evening. But for the poor Romans the worst was yet to come. During the night of August 24th and early in the morning of the 25th the volcano was shaken by heavy explosions and earthquakes while the ashes continued to burst out abundantly from the eruptive mouth, so as to surround Vesuvius in the early hours of the morning with an impenetrable curtain. Explosions around the crater became very strong and were accompanied by the emission of ash and gas clouds and the collapse of the eruptive column on the slopes of the volcano. Powerful pyroclastic flows formed, with speeds over one hundred kilometres (60 mi) per hour, in the direction of Herculaneum, Stabia, Oplonti and Pompeii. This last city, in view of its large number of inhabitants and the area it covered, was eventually the hardest hit by the eruption. The energy of the pyroclastic flows was such as to break down walls and destroy artefacts (Fig. 2.48a, b); Human bodies, those who were already worst affected by the collapse of the roofs or suffocated by the ash and those still alive who were attempting a last desperate escape, were further overwhelmed by the power of the flows, the temperatures of which exceeded 300 °C (572 °F). Many of these bodies were found in Pompeii during the various excavation campaigns beginning in 1748. The destructive power of the explosions had decapitated a part of the volcano. Most of the southern part of Vesuvius was completely submerged by pumice and ash. Where before there had been towns, roads, and cultivated land, silence and desolation reigned. It is difficult to estimate the victims of the disaster, but at least 2000 people lost their lives. The eruption of 79 A.D., like many explosive high-energy eruptions, develops in two main phases, the opening phase, characterised by the formation of an eruptive cloud and a rain of pumice and ash (pyroclastic fall) is subsequently followed by phreatomagmatic phase, characterized by avalanches of ash and incandescent gas (pyroclastic flow and pyroclastic surge) which flow at very high speed down the sides of the volcano. Its effects were felt up to several hundred kilometres away due to the ash transported into the atmosphere. The deposits of this eruption are found today in the entire southern sector of the volcano and partly in the northern area too as evidenced by the extent of the area affected by the explosion, on average with a radius of about six kilometres (4 mi) from the crater.

Pliny's writings on the 79 A.D. eruption have been carefully studied by historians, archaeologists and volcanologists to attempt to rebuild the various stages of the event, although the time elapsed between the eruption and the writing of the letters (several decades) produces a level of reasonable doubt that Pliny, in describing the various stages of the eruption, could have distorted the timeframe. A direct analysis of what Pliny wrote is not possible since we do not have the originals of the letters but what was transcribed in copies by amanuenses during the Middle Ages. One of these copies is kept in the Libraries of the Girolamini of Naples. Some doubts regarding the reliability of the amanuenses' transcripts have emerged with respect to the eruption date. Typically, this is referred to as the day of August 24th, "nine days before the September calendars," as one reads in one of the texts. It was, however, possible that, from time to time, the amanuenses would


(a)
Pyroclastic flow direction
Pumice fall
(b)
Pyroclastic flow deposit
Pyroclastic flow direction

◀ **Fig. 2.48** **a** Example of pyroclastic flow effects generated by the 79 A.D. eruption. This site, a Roman villa, is located within a quarry (Cava Ranieri) close to the town of Terzigno (east of Vesuvius), along the path of devastating pyroclastic flows. The sequence of volcanic events is very clear here. After the fall of pumice, the pyroclastic flow overwhelmed the interior of the villa. The columns were broken by the high dynamic pressure of the flow at the top level of pumice bed (the fallen columns also indicate the direction of the flow). The thickness of the pyroclastic flow is visible in the foreground **b**. Inside the pumice deposits (**a**) numerous terracotta shingles have been found, indicating the progressive roof collapse during the ash and pumice deposition (photo from Carlino and Luongo, 2005)

make mistakes in the transcription of texts, either by distraction, or the difficulty in decrypting ancient writings, often faded by time, for another transcription talks about November and not September. If that is the case then the eruption would have begun on 23rd October. The archaeological finds in Pompeii, Boscoreale and Oplonti have shown the presence of a range of quantities of foodstuffs such as laurel berries, walnuts, dried figs and prunes and pomegranates, all agricultural products whose ripening, harvesting and processing takes place in autumn and not during the summer. Even the grape harvest, which typically takes place in September, seems to have already been over for some time. This is documented by the numerous *dolia*, typical terracotta containers used for the preservation of wine, found, closed and sealed within a farmyard, and therefore already full of wine. These are indications of an eruption occurring in the autumn rather than during the summer, but not incontrovertible evidence. Another piece of evidence in favour of the autumn thesis was to be found in the House of the Golden Bracelet, in Pompeii, where a woman, still embraced by her son, held a bag with some small pieces of jewellery in her hand. Among them is a coin, on which is an abbreviation, a set of letters and Roman numerals, referring to the fifteenth acclamation of Emperor Titus (*salutatio iperatoria*), following his military victory. It is known from other written testimonies that Titus was acclaimed Emperor for the 14th time on September 7th and therefore a possible fifteenth acclamation could only take place later than this and therefore the eruption could not have taken place in August. Unfortunately, the denomination found on the coin does not appear clear, since it has been worn and oxidized over time, and thus the doubt remains. Although the exact date of the eruption may be considered a mere historical curiosity, the studies that have followed the archaeological excavations of Pompeii reveal new evidence of the eruption and interesting historical curiosities. In any case, as the scientific criterion prescribes, it is necessary to continue to consider August 24th as the day of the eruption, until unquestionable evidence can be found in favour of the argument of an eruption in the autumn.

2.9 The Most Recent Eruptions of Neapolitan Volcanoes

The final eruptions produced by the Neapolitan volcanoes took place in relatively recent times, in 1301–1302 on Ischia (the Arso eruption), in 1538 in the Campi Flegrei (the eruption of Monte Nuovo) and in 1944 of Vesuvius. The first two events are reported by historiographical testimonies, while for the eruption of 1944 there is a huge scientific and humanistic bibliography and the event was widely reported around the world.

2.9.1 The Arso Event on Ischia Island

At the beginning of 1300, the island of Ischia, which had recently joined the Kingdom of Naples, was under the guidance of the former Angevin (i.e. of the House of Anjou, the rulers of Naples at that time) ambassador to the Pontifical Court, Cesare Sterlich. The Ambassador found himself with the unexpected task of managing a volcanic crisis with the eruption of the Arso which took place between 1301 and 1302 in the eastern part of the island (the date of this event remains rather uncertain because of the few testimonies passed down to us). Historical eruption documentation, coupled with a geochemical analysis of the eruption's products, makes it possible to formulate some hypotheses about how the eruption unfolded. Although there are testimonies of historians describing the emission of large amounts of ash and pumice into the atmosphere and groundwater explosions, there is no mention of the earthquakes that commonly precede eruptive events although one event felt by the population was reported in 1302, in the east of the island. The historic and recent seismicity of the island of Ischia is typically associated with very superficial sources, between 1 and 2 km (about a mile) down, an element that makes earthquakes easily felt by the population, even when these are of low magnitude. The absence of reports of seismic events prior to the eruption of the Arso may therefore not necessarily correlate with their low magnitudes, but rather with the asismic behaviour of the rocks during the rise of the magma. The geochemical analyzes performed on the lava of the Arso, in particular the increase in the isotopic ratio of Strontium (Sr), also indicate the arrival of new magma from the deeper sources. The rising magma may therefore have intruded into an area of rheological weakness, where the stressed rocks react in a largely ductile manner. Such a hypothesis would be corroborated by the high geothermal gradients observed on the island (greater than 150° C/km), which lead to a shift towards the surface of the fragile-ductile rheological transition. This would explain the absence of earthquakes. The decompression of the magma during the climb would then release gas from the magmatic source, while its interaction with the groundwater levels encountered in the surface crust would have greatly increased the explosiveness of the magma. A ground explosion could then open the way for pressurized magma to exit, creating a first phase of the eruption characterized by the emission of very fragmented material, ash and pumice, which covered part of the eastern section of the island. This first phase of the eruption would have lasted for a couple of days, followed by a brief pause and then characterized by the emergence of a large amount of *scoria* (a dark-coloured igneous rock with abundant round bubble-like cavities known as vesicles) which formed a small crater near Fiaiano. In the last phase of the eruption, the magma, now very degassed, rose slowly to the surface, initially forming a stagnation dome and then overflowing north, until it reached the sea just to the east of the current Ischia harbour (Fig. 2.49). In this area

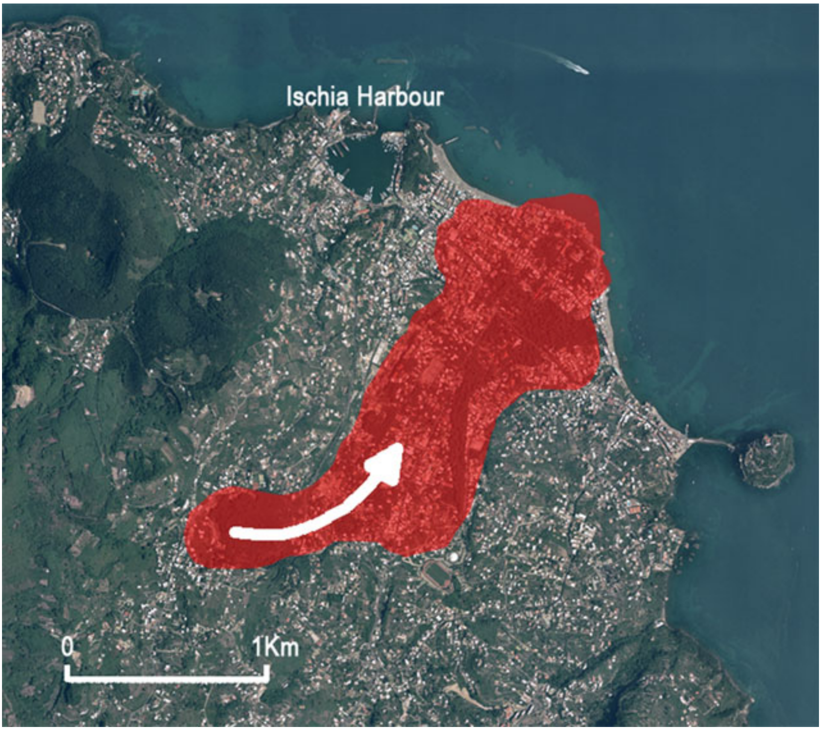


Fig. 2.49 The Arso lava flow produced during the last eruption on the Island of Ischia in 1302 (INGV-OV Archive)

the lava flow produced a broadened front which pushed into the sea for about 200 m, to form the present Punta Molino. This phase of the eruption lasted about two months. The Arso eruption caused several deaths, although the number is imprecise, and is described as a major catastrophe, an abnormal fact considering the very low energy of the event. This fact also supports the hypothesis of an eruption preceded by hardly any precursors, with no significant seismicity, which would have surprised the resident population. Likewise, the proximity of the eruptive centre to the inhabited parts of the island, in particular to the medieval town of Geronda, which was severely damaged, would have contributed to causing an abnormally high number of victims. Even the low perception of volcanic risk on the island (for about a millennium there had been no eruptions) would have led to an underestimation of the danger. This contributed to spread panic among the people for the unexpected event with the terrorized population deciding to escape by sea and finding shelter on the nearby island of Procida, and towards the mainland between Naples, Baia and Pozzuoli.

The Arso lava flow, today partially covered by buildings, is visible in some points along the two main roads leading from Fiaiano northwards to Ischia Porto. The flow is 2.7 km (1.7 mi) long and about 1 km (0.6 mi) wide at its widest point near the sea. In the upstream area it has a thickness of less than 5 m (16 ft), while at the terminal part it is between 15 and 17 m (50–56 ft) high. The lava flow is partly covered by a dense pine forest, planted in the Bourbon era, between 1853 and 1855.

2.9.2 A Major Ground Uplift but a Small Eruption: The 1538 Event at Campi Flegrei Caldera

Monte Nuovo is the results of the last eruption that took place within the caldera of the Campi Flegrei, in 1538, which in just two days produced a cone 133 m high, about 3 km northwest of Pozzuoli (Fig. 2.50). Involving some 20 million m^3 of magma, the Monte Nuovo eruption took place on the western side of the uplifted block of La Starza, which has been affected by volcanic-tectonic movements for about the last 8,000 years. This is the only historical account of an eruption, possibly one of the smallest on record in the Campi Flegrei, which, even so, is fundamental in improving the knowledge of the behaviour of a caldera.

The accounts of the 1538 eruption are different from those reported for the eruptions of Vesuvius which was active in Medieval times. The culture during the 16th century, the era of Renaissance, was characterised by a major interest in the features of natural world. In this historical transition, thought was no longer

Fig. 2.50 Monte Nuovo (located between the Averno lake and Lucrino) is a 133 m high crater formed during the last eruption of the Campi Flegrei in 1538 (from CAI, Club Alpino Italiano)

exclusively “biblical” and, in this sense, the witnesses of 1538 eruption reported the first fairly reliable description of an eruption in historical time. At that time the Spaniards were in charge in Campania and most of southern Italy. Pozzuoli and Naples were two very important cities with some 20,000 and 250,000 inhabitants respectively. The port of Pozzuoli was flourishing and the city was a very pleasant place to live with the same advantages that had graced other places such as Herculaneum, but further from the hazard of volcano, although not for a long enough time!

The Campi Flegrei formed fertile and flourishing soils, with the main centre in Pozzuoli and with small villages scattered along the surrounding rolling hills, including Tripergole, famous for its thermal baths and a tourist destination. This village was to be the one hardest hit by the eruption.

The signs of the eruption, although not understood as such, manifested themselves many years before, with the lifting of the ground and earthquakes. The latter were reported and clearly felt by the population and included 25th May 1469, 11th August 1475, 31st July 1488, 9th November 1469, 18th March, 1499, 18th May, 1505, and 15th January, 1508. Some of these events, such as that of 1488, were particularly intense and caused serious damage to buildings near the epicentre. The seismic activity intensified in the first decade of the 16th century, generating concern and fear in the population, who were not aware that these events could be precursors of an eruption.

There are several testimonies to the earthquakes, such as the one reported by Cola Aniello Pacca, at Easter on 4th April 1534:

> "*In the end of the Sabbath, as it began to dawn toward the first day of the week, came Mary Magdalene and the other Mary to see the sepulchre. And, behold, there was a great earthquake: for the angel of the Lord descended from heaven, and came and rolled back the stone from the door, and sat upon it*".

The increase in seismic activity was also discussed by the Neapolitan doctor Simone Porzio, who wrote about the powerful earthquakes that shook the area around Pozzuoli: "*no house remained undamaged and all the buildings seemed threatened with certain and imminent destruction*". With the increase in seismic activity, there is also a rapid increase in the speed of soil lifting in the Pozzuoli area.

The historical trend of ground movements within the Campi Flegrei has been inferred since Roman times by observing the signs left by date mussels *Lithophaga lithophaga* on the columns of the Temple of Serapis, which provide a rough reference of sea levels and their variation over time - a 'date mussel' used to date sea level change. According to various studies, from at least 2,000 years ago the paving in the Temple of Serapis subsided at a rate of tens of millimetres per year, reaching a maximum submersion of the Pozzuoli area in the 13th century. At that time an inversion in ground movements occurred, with a slow uplift at a rate similar to that of the preceding subsidence, followed by the onset of sustained uplift a few tens of years before the 1538 eruption (Fig. 2.51). The marble paving of the Temple of Serapis had remerged, close to sea level by 1503 when a royal edict ceded the new land that had emerged offshore from the harbour to the town of Pozzuoli, but no one imagined that the appearance of the new beach might be a precursor to an eruption in less that 40 years. A maximum uplift of about 20 m (66 ft) occurred during that time, prior to the 1538 eruption. In the years running up to the eruption, continuous earthquakes were felt by the population of Pozzuoli and Naples, as mentioned by Marco Antonio delli Falconi (1538) and Pietro Giacomo da Toledo (1539): "*…it is now two years that there have been frequent earthquakes at Pozzuolo, at Naples and the neighbouring parts; on the day and in*

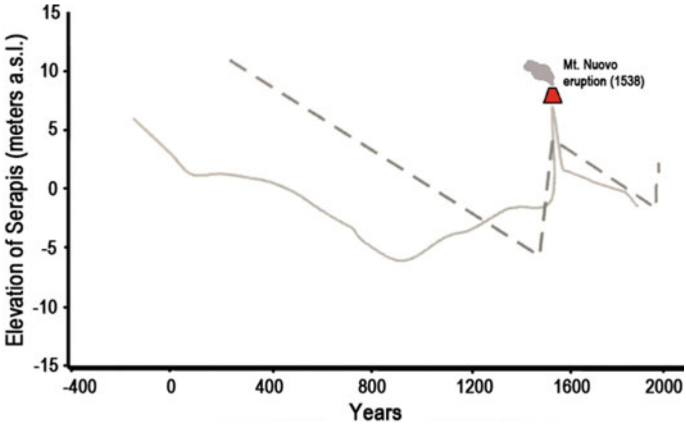


Fig. 2.51 A reconstruction of the subsidence and uplift phases (bradyseism) of floor of the Serapis temple (Pozzuoli), since Roman times, deduced from the observation of the sea level variation. The latter has been inferred from the study of the signs of marine molluscs left on its columns. The solid line is the reconstruction according to Parascandola (1947) while the dotted one is from Dvorak and Mastolorenzo (1991)

the night before the appearance of this eruption above twenty shocks great and small were felt at the abovementioned places…"

The level of tremors increased dramatically on Friday 27th September 1538. Water, steam and mud were discharged from cracks close the village of Tripergole, a sign related to the magma rising to the surface and its interaction with groundwater. While the earthquakes reached their climax between Friday 27th and Saturday 28th September, the rapid uplift of the ground at Pozzuoli produced a retreat in sea level leaving large numbers of fish stranded on the sand. This was seen as manna from heaven by the fishermen of Pozzuoli, but it wasn't. On the contrary it was a cruel diversion. In fact, a few hours later, when the rising magma mixed with the groundwater, a violent hydromagmatic eruption took place on Sunday 29th September. The priest, Delli Falconi, reported that an hour or two after sunset, molten rock burst out from cracks near the sweating rooms in the spa of Tripergole village. Other witnesses said that the eruption had started close to the hospital in the Fumosa Boulevard not far from the sea. There are no accounts of deaths during the opening phase of the eruptions, because the clear signals of danger were observed a few days before it occurred and people had abandoned the village. This opening phase was characterized by the occurrence of small pyroclastic flows, covering a very limited area. Later, accumulations of ash and the scoria of fragmented magma, expelled by the new vent, produced a cone that buried the village of Tripergole within 48 h. People were panicked not only when they had left home due to the earthquakes, but particularly when the ash from the eruption began to fall in the surrounding area, as Delli Falconi recounted: "*The poor citizens of Pozzuoli were terrified by such a horrible spectacle. They abandoned their houses, which had been filled by the ashy and muddy rain that had continued over the whole area and throughout the day. Fleeing from death, but with the colours of death painted on their faces, they guided their terrified families towards Naples, some with their children in their arms, some with sacks filled with their possessions, others leading a laden donkey. Yet others were carrying birds of all sorts, which had fallen dead in great numbers when the eruption began. Others took away stranded fish, which they had found a-plenty on the dried-up shore*". Thousand of scared and exhausted people rushed into Naples, where the inhabitants heard the explosions of the eruption like gunfire. Meanwhile ash covered many buildings in the city and formed a carpet about 2 cm thick along the streets.

The volcanic activity was intermittent, with minor explosivity and some more intense Strombolian explosions. On Monday September 30th the Viceroy, Pedro de Toledo, visited the site of the disaster and acknowledged that he was unable to act against Nature. He had been correctly careful in keeping a safe distance from Monte Nuovo, the new volcano which had built up in two days, because the hill still showed signs of activity with fearsome noises, as well as ash and blocks being expelled from the crater. The decrease in activity over the first few days of October encouraged witnesses of the event to climb the new cone along a small south-facing gulley a week after the initial eruption on Sunday 6th of October. Hydromagmatic activity is often very intermittent, with unpredictable explosions alternating with periods of apparent quiescence. The unknown nature of such volcanic phenomena was unfortunate for the climbers. They encountered the final explosion that brought the eruption to a close and twenty-four people were killed before they reached the crater rim by an incandescent flow of scoria which swept down the gulley they were climbing. This terrible moment was described by the Delli Falconi: "*Some people had climbed half way up the mountain, and others has reached a little farther up, when, about the twenty-second hour [4 p.m.]. such a fearsome and sudden conflagration arose with such a great mass of smoke, that many of these people were suffocated; and many were never found, dead or alive. I was told that those who were killed and those that were not found at all, amounted to more than 24 in number. There have been no notable effects since then, but the activity seems to come back from to time like the ague and the gout*". After this dramatic episode the activity of Monte Nuovo quickly became dormant and an inversion in ground uplift was observed with a slow subsidence which lasted at least 400 years, after which renewed uplift began once again in late 1969.

The first reaction that the inhabitants of Pozzuoli immediately after the eruption of 1538 was to abandon the places of the disaster and make their way to safer areas. The eruption was an event that today can be classified as being of small-moderate energy (VEI = 2) but, despite this, it was able to cause damage due to its proximity to various population centres. Damage was also wrought by the earthquakes and the strong deformations undergone by the ground, which preceded the paroxysmal event. The Viceroy immediately demonstrated his intention to rebuild the places that had been destroyed, in particular by laying down new roads and new buildings in Pozzuoli. It is interesting to note the attention that the Viceroy placed on not wanting to leave places affected by the eruption desolate as described by his biographer Scipione Miccio: "*The Viceroy, who was unwilling to consent to the desolation of such an ancient city that was of such use to the world, decreed that all the citizens should be repatriated and exempted from taxes for many years. To demonstrate his good faith, he himself built a palace with a fine strong tower, and erected public fountains and a terrace a mile long with many gardens and springs. He reconstructed the road to Naples and widened the tunnel so that it could be traversed without lights. He built the church of San Francisco at his own expense. He also restored the hot baths as successfully as possible, and had the city walls rebuilt. And, to stimulate interest in the city, he decided to spend half year in Pozzuoli, although ill health subsequently enabled him to stay there only in the spring*".

The determination of the Viceroy was commendable, even if the return of the inhabitants to Pozzuoli was gradual, partly due to the damage suffered by many of the buildings and partly because the population feared a repetition of the event. Monte Nuovo continued to spew smoke and fumes for several years, probably until the end of the eighteenth century, when weak fumarolic activity was still observable inside the crater.

The volcanic cone of Monte Nuovo is nowadays visible along the shoreline of Lucrino, between Pozzuoli and Baia, and is covered by luxuriant vegetation. A walk along the small crater is allowed by following the trail of the "*Oasi Naturalistica di Monte Nuovo*". Here one can observe the whole spectrum of the products ejected during the 1538 eruption and the site also offers a fine panorama of the western side of the Campi Flegrei, along with Pozzuoli, Baia, Capo Miseno and the island of Ischia (Fig. 2.52).

Fig. 2.52 The volcanic scoria forming the flank of the Monte Nuovo crater. The structure and the deposits of this small eruptive centre are visible along the "Oasi Naturalistica di Monte Nuovo" at Lucrino (between Baia and Pozzuoli) (photo A. Fedele)

2.9.3 Vesuvius During the Second World War: The 1944 Eruption

Vesuvius closes its history as an "active" protagonist of the events surrounding Naples with the final eruption of 1944 towards the end of World War II. With the arrival of Anglo-American allied troops and the liberation from the oppression of the German army, volcanology in Naples was to be the interpreter of the last phases of the world conflict. It fell to Giuseppe Imbò, then director of the Vesuvian Observatory, to draw up the reconstructions of the eruptive phases, which were transcribed amidst a thousand difficulties, while the observatory itself was requisitioned by Allied forces to create a strategic military site. Imbò carefully followed the evolution of the volcanic phenomena within the crater where the effusive eruptions, which occurred during the previous eruptive period had begun in 1913, having filled the crater cavity and forming an apical cone from which the characteristic plume of smoke emerged (Fig. 2.53). A few years earlier, small lava flows were emitted by fractures at the base of the cone, with phenomena which intensified for about a month. The director of the Vesuvius Observatory considered

Fig. 2.53 A view of Vesuvius from the "*Osservatorio Vesuviano*" during a rest phase in 1930. The characteristic plume was a permanent indication of the open conduit activity from 1631 to 1944 (courtesy G. Ricciardi, from "*Diario del Monte Vesuvio*")

these events as prodromal to a stronger eruption that might occur from there in a few years and that would have closed the eruptive period begun in 1913, but not the long eruptive cycle that began in 1631. More than seventy years on, we can say that Imbò was only partially correct. Since then, Vesuvius seems to have entered a quiescent period that seems very long with the closure of the cycle that began in 1631, and which could restart with an explosive eruption.

In those years the war irrupted powerfully into the Vesuvius Observatory's affairs, when in December 1943, Imbò was, to all intents and purposes, forced to sign a requisition agreement of most of the observatory's buildings for use by the Allied Forces. Only a few spaces were provided to continue the Observatory's work of surveying volcanic activity. Despite his insistence on the need to have more space and resources available because of the danger of an eruptive event, he was told (it was an Italian American lieutenant to do so): "volcanology is not needed in wartime." Soon the allied troops had to eat their words when, on 18th March 1944 Vesuvius erupted. Already from the early days of January, new fractures had been observed on the eruptive cone with weak lava emissions. These phenomena diminished in intensity until 13th March, when the partial collapse of the cone also caused a momentary interruption of the smoke plume coming from the crater. The eruption began in the late afternoon of the 18th March when a large ash cloud was observed, rising from the crater and bending northwards. The American contingent, this time worried about what was happening, provided Imbò with a military truck to go to the highest part of the volcano, towards the *Atrio del Cavallo*. Strombolian activity was observed with the formation of a lava lake around the cone. These first observations were transmitted to the Prefect through a letter, since any other type of communication (telephone or telegraphic) had been interrupted, but without any reply. Only afterwards was Imbò allowed to use the communications equipment of the US military command. Meanwhile, on 19th March the effusive activity intensified, with the formation of a lava flow from the north side of the crater, diverted westward towards the *Atrio del Cavallo*, and on the 21st March invading the villages of San Sebastiano al Vesuvio and Massa di Somma while also threatening Cercola (Figs. 2.54 and 2.55). The lava flow, however, definitively stopped on the 22nd when the nature of the eruption had already changed and now was characterized by a strong degassing phase, already with the formation of large lava fountains by the 21st. The most intense phases of explosive activity produced the launch of scoria and lapilli to a height of over 1000 m (3200 ft). This activity worried the military serving at the Observatory, many of whom left the headquarters during the night of 21st. However Imbò remained in the HQ along with his wife, the Observatory caretaker and some *carabinieri*. We do not know if the director of the Observatory was certain that the eruption would reach the paroxysms that would have endangered their lives, but in fact this attitude produced some confidence and hope in the positive evolution of the phenomenon. At about midday on the 22nd the activity of the volcano changed again with the formation of a dense cloud of dark ash, which reaches a height of about 5 km (3 mi) together with explosions associated with the launch of scoria and volcanic bombs. This activity was followed by a brief moment of apparent calm, which also allowed some observations on the morphological changes of the volcano to be made.

On the 23rd March a new explosive phase began, accompanied by intense seismic activity, producing small pyroclastic flows on the volcano's sides, while the eruptive cloud moves upward and the winds at altitude moved the ash cloud eastwards (Figs. 2.56 and 2.57). Many of the bombers stationed by the Allied Forces Air Command at the Terzigno Airfield were irretrievably damaged by the accumulation of ash. In the following days, from 24th March onwards the

Fig. 2.54 The vapour emitted by the lava flow on Vesuvius in 1944 along the "*Atrio del Cavallo*". The lava flow passed close to the building of the "*Osservatorio Vesuviano*", in the foreground, at Colle Umbero (courtesy G. Ricciardi, from "*Diario del Monte Vesuvio*")

explosive activity continued with alternating phases, the decreasing pressure of the magmatic feeding system causing a gradual lowering of the column of magma in the duct, with collapses within the crater cavity taking place on the days of the 27th, 28th and 29th March. These are prodromic phenomena of a reduction of the energy of the eruption, which on 7th April 1944, with the complete closure of the duct, could be considered over and with it the long cycle of activity which had begun in 1631. The eruption caused most damage to San Sebastiano al Vesuvio

Fig. 2.55 A photograph of the explosive phase of the 1944 Vesuvius' eruption taken by the Allied Air Force (courtesy G. Ricciardi, from "*Diario del Monte Vesuvio*")

and Massa di Somma, in the eastern sector of the volcano, where the lava invaded and destroyed several buildings and communication routes. Despite the preventive evacuation of the lava-threatened towns, 26 casualties were counted, some of which, including two children, were killed by the explosion of a tank overheated by the passage of lava. Other people were hit by the collapse of roofs weighed down by ash and the rain of lapilli. Since then, Vesuvius has been quiescent and is characterized by seismicity of a very low energy, with two major magnitude seismic episodes occurring in May 1964 and in October 1999.

Fig. 2.56 A view from Naples of the ash column, about 6 km high, formed during the explosive phase of the 1944 Vesuvius' eruption (courtesy G. Ricciardi, from "*Diario del Monte Vesuvio*")

Fig. 2.57 Another spectacular view from Naples of the ash column produced during the explosive phase of the 1944 Vesuvius' eruption (courtesy G. Ricciardi, from "*Diario del Monte Vesuvio*")

2.10 The Heat of Volcanoes and Hydrothermal Activity

Volcanoes are the surface evidence of the heat contained in the Earth's interior. The average temperature gradient, that is the increase in temperature with depth into the crust, is about 30 °C/km (138 °F/mi). This average value is associated with the latent heat of the Earth and the heat produced by the radiogenic decay of certain elements, such as Thorium and Uranium, contained in the Earth's crust. Larger geothermal gradients are indicative of volcanic-tectonic processes affecting the Earth crust, which increase the amount of heat transported to the surface. The increase in a geothermal gradient on large scale is typically due to the thinning of the Earth's crust beneath the oceans, where the discontinuity between the rigid crust and the partially-melted upper mantle, the Moho, is closer to the surface. At

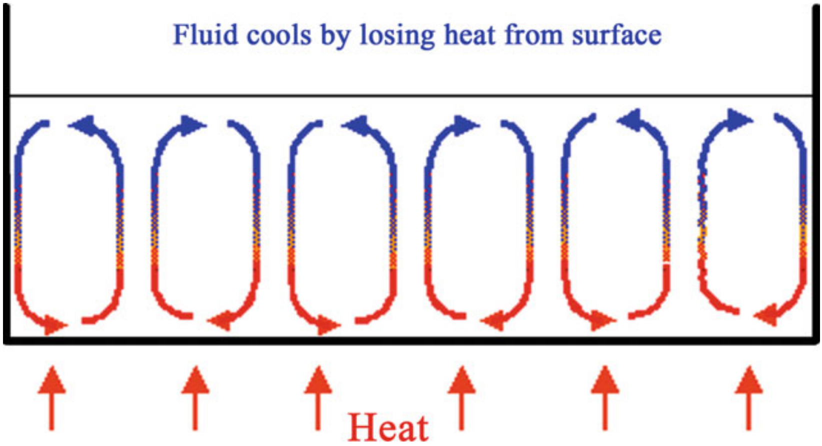


Fig. 2.58 While the process of heat transfer by conduction from a warmer to a colder body is slow, convection (or advection) is more efficient and rapid. The former process, in fact, involves microscopic collisions of particles and movement of electrons within a body. For example, the time (t) required for the conductive propagation of temperature changes at a certain distance (l) from the source is equal to l^2/k (k = thermal diffusivity). Let us take for instance a magma chamber located at a depth of 10 km, and fixing a thermal diffusivity $K = 10^{-6} m^2 s^{-1}$, we obtain that t = 3 My. As shown in the figure, the convective heat transfer is more efficient because it involves the mass transport of fluids. In brief, the carrier fluid, which is heated from below, becomes less dense than the surroundings and rises as a result of buoyancy. The process continues by the cooling of the fluids when it reaches the surface, with an increase in density and its subsequent re-sinking. This finally forms a convective cell. The amount of fluid advection in a volcanic geothermal system is strictly correlated to the permeability of rocks and to the temperature of its magmatic source

local scale (a few kilometres) a further increase in the geothermal gradient with respect to the normal situation is associated to the migration of magma into the shallow crust and the activation of advection fluids lying above the magma sources. Heat contained in the magma reservoirs is, in fact, transferred to the surface by conduction and/or convection (advection) processes (Fig. 2.58). The former, which is related to the vibration of atoms composing the matter, is a slow process which means that the heat takes long time to move into the rocks, passing from the heat source to the surface. Thus, large and deep magma chambers take hundred-thousands to millions of years to lose all their heat if cooling only takes place by the conduction process. Otherwise, the heat transfer is accelerated when fluids take part in the thermodynamic processes, so that this “mass transfer” carries the heat faster towards the surface. For instance, if the rocks above a hot magma reservoir are saturated with water, and the dimension of the reservoir is large enough, advection takes place and an overheated and low-density water-vapour mixture moves and transports the heat to the surface. At this point a part of heat energy and mass is discharged at the surface by fumaroles and hot springs and by other spectacular volcanic manifestations such as mud-pots and geysers (Figs. 2.59 and 2.60). The set of components consisting of the magma reservoir, water saturated rocks and gases and heat discharge systems from the ground, forms a volcanic geothermal system. Hydrothermal manifestations are very intense at the Campi Flegrei and on the island of Ischia and have been well known since the Roman times for their use as thermal baths. The crater of Solfatara, inside the Campi Flegrei caldera, is the site with the most powerful manifestations. This area is characterised by widespread soil degassing and the presence of hot fumaroles and mud-pots. These fumaroles reach a maximum temperature values of around 160 °C (320 °F). On the eastern external side of the Solfatara crater, at Pisciarelli, there is another intense degassing area with high fumarole temperatures.

The Campi Flegrei caldera and the Island of Ischia are two classic examples of volcanoes in which the geothermal system is dominated by advection fluids

Fig. 2.59 Geysers represent one of the most spectacular manifestations of active geothermal systems. The Old Faithful Geyser within the Yellowstone caldera (U.S.A) is the most famous example (photo Janet Jones, yellowstonenaturalist.com)

Fig. 2.60 The Solfatara mud pool within the Campi Flegrei caldera. This area is characterised by the presence of numerous emissions from fumaroles and mud-pots (photo S. Carlino)

(water + vapour). The temperature profiles measured inside the deep wells at Campi Flegrei and Ischia, show the presence of advection zones with constant temperatures associated with a large circulation of fluids. The geothermal gradients of these areas range from 150 °C/km (486 °F/mi) to 250 °C/km (775 °F/mi). On the other side of the Campi Flegrei, Vesuvius is a "colder" volcano, and the mechanism of heat transfer, from the magma source to the surface, is perhaps mainly dominated by conduction. In fact, a measurement of temperature from deep drilling (the Terzigno well) located few kilometres east of the crater showed a "normal" geothermal gradient of less than 30 °C/km (138 °F/mi) (Figs. 2.61 and 2.62). The lack of a large geothermal system, such that found in the Campi Flegrei and on Ischia has not allowed the mass transportation of hot fluids from the deeper part of the volcano to the surface. Circulation of hot fluids and vapour occurs only along the central axis of volcano while weak fumarole activity is recognizable at the top of the crater. The difference in these thermodynamic behaviours, the hotter

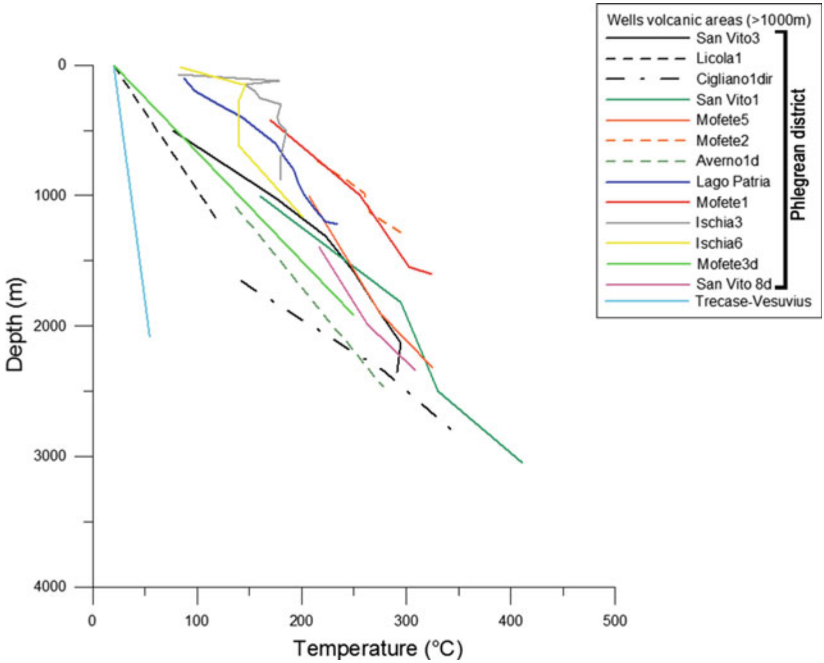


Fig. 2.61 Temperature versus depth measured during deep drilling in the Phlegraean volcanic district and Vesuvius (from AGIP, 1984). As the temperature profiles shown, the Phlegraean district (the Campi Flegrei caldera and Ischia) is very hot, while the temperature-depth trend recorded at Vesuvius, (in the Trecase well) about 4 km east to the crater axis, is equal to the normal gradient for continental areas (about 30 °C/Km) (after Carlino et al., 2012)

Ischia and Campi Flegrei districts and the colder Vesuvius one, is respectively related to their differing deep structure and dynamics. Large explosive hydro-magmatic eruptions at the Campi Flegrei and Ischia calderas produced intense damage to the rocks and hot magmatic fluids rose from magma chambers to the surface and towards fractured and permeable rocks. The minor magma reservoirs are relative shallower at Campi Flegrei and Ischia and are hot enough to produce the advection of heated fluids and the transition from brittle to ductile behaviour of rocks at depths of few kilometres. This transition generally occurs at temperatures of 350–450 °C (660–840 °F) for volcanic rocks. The shallow magmatic system of Vesuvius, located at a depth of around 4 km, is formed by a colder

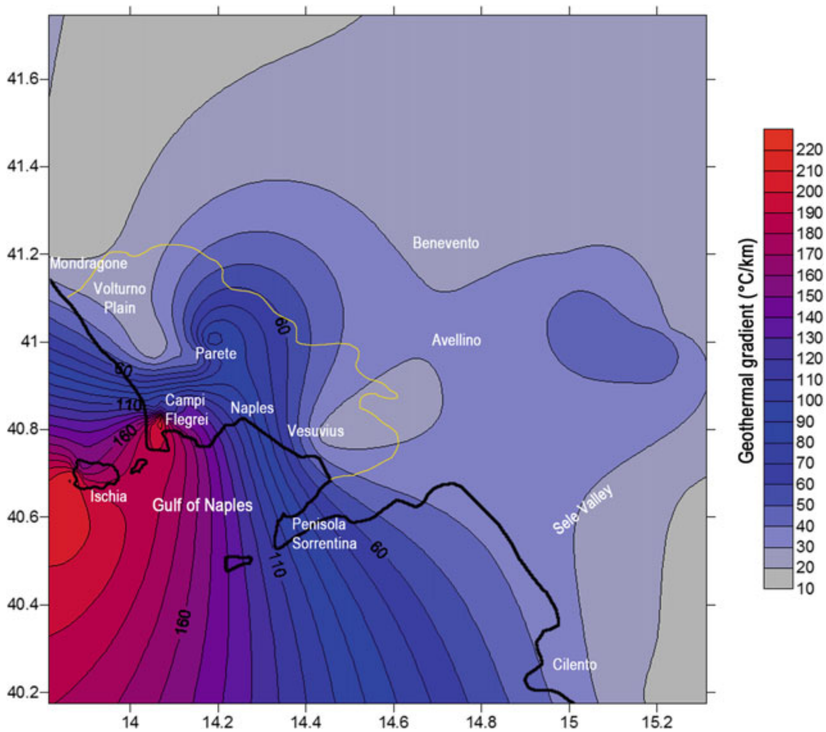


Fig. 2.62 Map of the geothermal gradient of Campania region obtained from temperature data of wells > 1 km in depth. The yellow line represents the boundary of the Campania Plain. The main thermal anomaly is confined to the area between Ischia and the Campi Flegrei caldera indicating the presence of magma sources at depths that are responsible for both the thermal disturbances in the crust and the activation of advection fluids

system of conduits with minor heat content, thus avoiding the activation of the large-scale advection of fluids. The deeper and partially melted magmatic system of Vesuvius, possibly located at a depth of about 8–10 km (5–6 mi), is perhaps isolated from the shallower crust by a large sequence of dolomitic rocks. We will also see in the last chapter of this book that degassing and large geothermal manifestations of volcanoes, when compared to colder volcanoes, are not necessarily related to a higher risk of eruption. In any case, these manifestations have proved a fortune for people living around Campi Flegrei and on Ischia where the

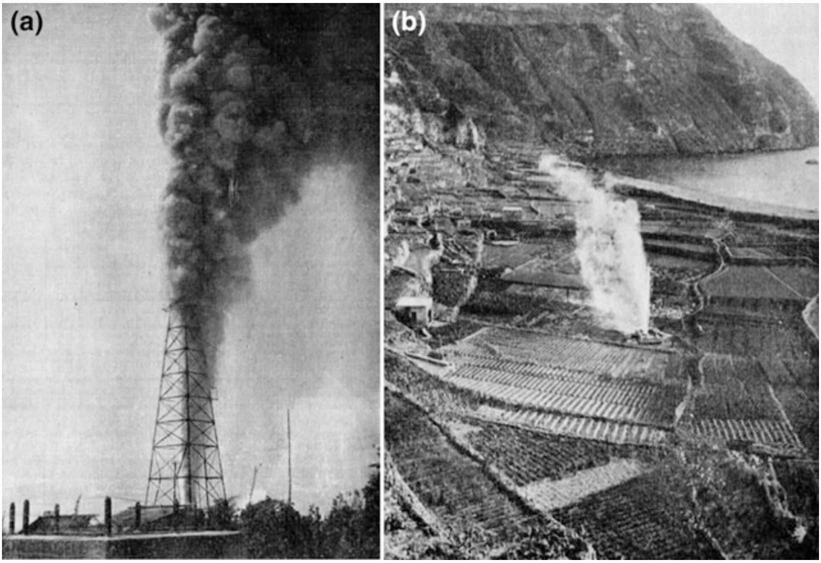


Fig. 2.63 **a** A test for geothermal exploitation in the western part of the Campi Flegrei (Mofete) and on the western sector of the Island of Ischia (Cetara) **b**, during the AGIP-ENEL drilling campaign in 1940 (from Penta and Conforto, 1949)

heat of the soil has made these areas very famous for thermal baths since Roman time and later for the development of the spa industry. The heat output of the Neapolitan volcanoes is also a potential resource for producing thermal and electrical energy. Thermal energy is commonly utilized on the island of Ischia for the house heating, while geothermal exploitation for electricity production has not yet been developed (Figs. 2.63a, b).

Appendix A, B and C

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3 Volcanoes and Human Settlements

In no part of the globe do the relationships of geography and history form such a dense and intricate plot as they do in the Mediterranean. To understand humans and places, one must consider the persistence of natural conditions and the continuity of human effort.

(Orlando Ribeiro, 1968).

A view of Neapoletain volcanic distric from the Eremo dei Camaldoli (Photo A. Fedele)

S. Carlino, *Neapolitan Volcanoes*, GeoGuide,
https://doi.org/10.1007/978-3-319-92877-7_3

3.1 The Colonisation of Campania

> "*From Sinuessa, the coast extending up to Miseno forms a large gulf and then another gulf, much larger than the first, called the Crater, which extends between the two headlands of Miseno and the Athenaeum. This coastline takes in the whole of Campania, the most favourable plain of all, surrounded by fertile hills and the mountains of the Samnites and the Osci.*"

Thus the great Greek geographer Strabo, in his work, *Geography*, who lived between 64 B.C. and 19 A.D. described the coast of the Piana Campana in the stretch from Sinuessa, a city in Lazio to the borders of Campania as far as Punta Campanella. It is also eloquent that at this time the word *Cratere* (Crater) was used to denote the structural depression of the Campanian plain overlooking the gulf of Naples between the island of Capri, to the west, and the island of Ischia to the south-east.

The history of these places is inextricably linked to the myth, in the presence of often ghostly environments and ancestral aspects that have stimulated the imagination of poets and writers; places dominated by fire and continuous puffs of hot steam. Along the Lake of Averno (Fig. 3.1), immediately northwest of Monte Nuovo, the ancients placed the cave of the Cumaean Sibyl (Fig. 3.2) and the entrance to the afterlife, crossed by Ulysses and Aeneas and it was with the Averno, at a later time, that they went on to designate the underworld of the dead, precisely because of the foreboding atmosphere that the landscape communicated to humankind. This crater-lake exhaled vapours and volcanic gases that probably kept some animals away, from which it got its Greek name, *aoèrnov*, that is, "without birds".

The geology and landscape of Campania were undoubtedly the main attractions for the populations that colonised this area, the Romans calling it *Campania felix* (from the Latin *felix* = lucky, happy), not only for the beauty of the places, but for the fertility of the soil coming from the volcanic activity, the presence of streams and the gentleness of the climate. The broad river and coastal plains, the modest mountain ranges overlooking them, the steam and the various volcanic areas, the thermal waters and natural coastal inlets to protect the sailors all combined to transform the area into the crossroads of different civilizations. Societies, cultures, political, scientific and artistic experiences along a slow and steady path, mingling, meeting up, stratifying and bequeathing unique and extraordinary testimonies that make Campania one of the most complex territories in Italy and one of its richest Regions from an archaeological, historical and artistic perspective.

Fig. 3.1 View of the Averno Lake from the northwest. In Virgil's *Aeneid*, it is from this lake that Aeneas descends into the underworld. It was believed to be the Gates of Hell. It's hard to imagine hell in such a bucolic setting, but possibly, thousands of years ago, there were abundant fumaroles around the lake, making this picture more spectral (photo A. Fedele)

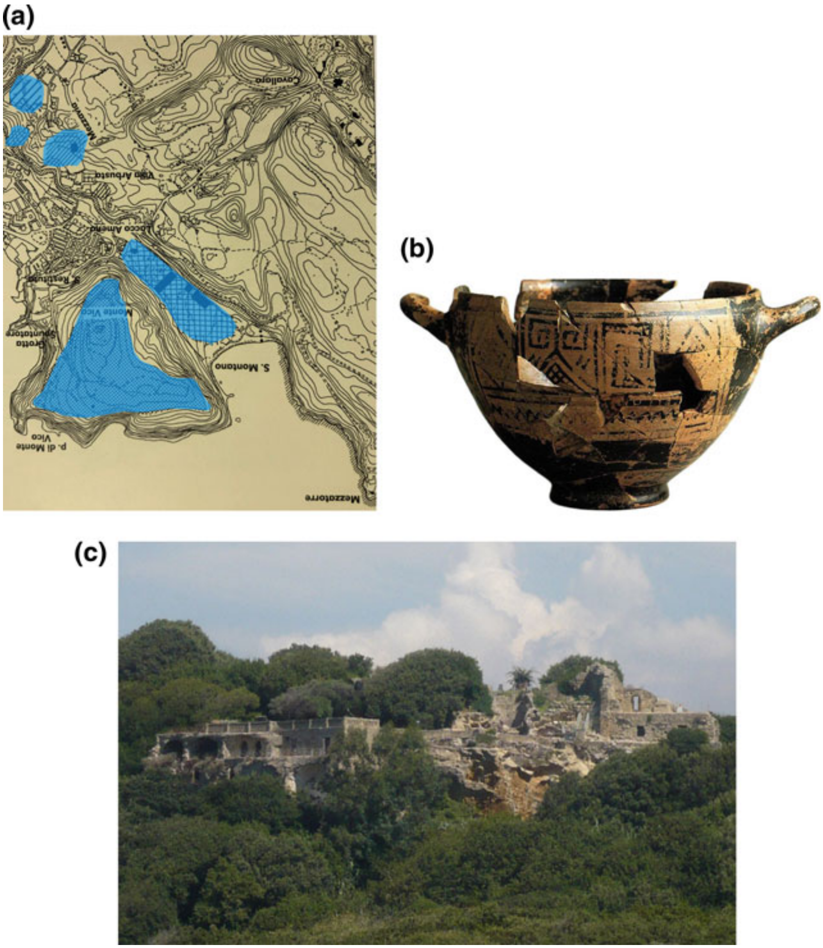
It would seem that the first and most ancient human settlements in Campania date back to the Palaeolithic, mainly along the coasts of the Sorrento Peninsula. Of great importance, however, was the discovery of an ancient Bronze Age village (dating back to the second half of the 3rd millennium B.C.) near Nola, about 11 km north of Mount Vesuvius, where archaeological excavations have uncovered huts equipped with many furnishings and animal remains (Fig. 3.3) in a state of excellent conservation. It was Vesuvius that, following a massive explosive eruption that occurred 3,800 years ago, sealed the village beneath its ash in a fate similar to that which befell Pompeii a few thousand years later. The finds of another village near Sarno (Longola di Poggiomarino), about 10 km east of Vesuvius belong to a later period, from the middle of the 2nd millennium B.C. through to the Iron Age which was built in a marshy area, formed by the Sarno River, and seems to have had about a thousand inhabitants and was equipped with metal and ceramics workshops.

Fig. 3.2 The *Antro della Sibilla Cumana* (The Cave of the Cumaean Sybil), near the Archaeological Park of Cuma, is a long Graeco-Roman tunnel entirely carved out of the tuff. In this area a colony was founded which spread Greek culture in Italy. Besides its historical importance, the site is linked to the myth of the Cumaean Sybil, already mentioned by Virgil in the third book of the Aeneid, when Aeneas, in order to find the land destined for his people by the gods, must go and interrogate the oracle of Cuma. According to the myth, it was here that the Sybil operated and disseminated her "oracles", which, for the Roman people, were pieces of advice to be heeded or revealing prophecies (photo A. Fedele)

The presence of Etruscan populations, who, moving down from central Italy, occupied Campania from the 9th to the 5th century B.C. when they were defeated by the Samnites, was fundamental, as they constructed the first early urban centres, in the area of the present city of Capua to the north of the Campi Flegrei. These populations predominantly settled in the fertile lowlands of the Campanian Plain, along the rivers or close to their river-mouths. With the establishment of the first maritime trade, especially by the Greeks, the inhabitants of Campania migrated towards coastal areas and began to settle in the volcanic areas of the Campi Flegrei, Ischia and Vesuvius. It was this complex morphology of the volcanoes, with their natural inlets and bays, which allowed the landing of the first Greek boats and, later, the establishment of the Roman naval fleet at Lucrino, in the Campi Flegrei. The Greeks, who arrived between the 9th and the 8th centuries B.C., came mainly

Fig. 3.3 Archaeological excavation of the Bronze Age from the city of Nola (from Archeoblog.net)

from Euboea, a large, long and narrow island close to the coast of modern day south-east Greece. They first occupied the Isle of Ischia, later moving on to the *terra firma*, when, in the 8th century B.C., the Cuma colony was be founded in the Campi Flegrei (Fig. 3.4a, b, c). The geographer and chronicler Strabo describes Ischia, at that time called "*Pithecusae*" thus: "*Pithecusae was colonized by Eretrians and Calcidians, who, although they prospered given the fertility of the soil and the gold mines, abandoned it (first of all) because of the discord between them and then later as well because they were terrified by the earthquakes and the eruptions of fire, of the sea and hot water. The island is in fact subject to such emanations, so that even the new settlers sent by Hieron, the Syracuse tyrant, abandoned both the fortress they had built and the island which was reached and then occupied by the Neapolitans. From here the legend spread that Typhon* (a monstrous serpentine giant and the most deadly creature in Greek mythology) *lies*


(a)
(b)
(c)
S. Montano
Monte Vico
S. Restituta
Lacco Ameno
Vico Arbusta
p. di Monte Vico
Mezzatorre

◀ **Fig. 3.4** **a** The first Greek settlements on the island of Ischia and in the Campi Flegrei (Cuma) (After Pappalardo, 2006). **b** The Cup of Nestor is an important archaeological find discovered in 1954 by Giorgio Buchner during excavations in the area of San Montano, on the Island of Ischia. It was the same archaeologist who personally composed the fragments of the cup that gradually emerged from the excavation work. On this is engraved an epigram that today is the only example of writing contemporary to Homer's Iliad. The Cup of Nestor is located at the Archaeological Museum of Pithecusae, set up within the Villa Arbusto in the municipality of Lacco Ameno (photos www.fotoweb.it). **c** The Cuma acropolis is an important archaeological site that, together with Ischia, was the first of the western Greek settlements. The acropolis stands on a small relief (about 80 m above sea level) consisting of a dome of very ancient trachyte lavas, formed during the eruptive activity preceding the Ignimbrite Campana (39,000 years ago). In this area there are also tuff deposits of the post-caldera activity. It would seem that the founders of Cuma were the Euboeans of Calcis (in Central Greece). Although linked to a maritime and commercial tradition, the settlers of Cuma found fertile lands in this area, which they also used to expand their economic and political power. The acropolis of Cuma, together with the Cumaean Sybil's Cave, is a tourist attraction of considerable interest

beneath this island, and that when he stirs, flames and water emerge, and sometimes even small islands with boiling water."

It was mainly the great Italian–German archaeologist Giorgio Buchner (1914–2005) who discovered the oldest settlements of prehistoric populations on Ischia and the first Greek colonies. Buchner had been fascinated from an early age by the island, which he had also learnt about through the writings of the historian Julius Beloch (1854–1929), describing the numerous finds of ancient human settlements found in the San Montano area of Lacco Ameno. In 1949 Buchner became an official of the Archaeological Superintendence of Naples with responsibility for Ischia and initiated excavations, first in the area of Castiglione and then in Lacco Ameno, where finds dating back to the Greek colony of Pithecusa were discovered from around the 8th century B.C. It was Buchner himself who discovered the Cup of Nestor at the necropolis of San Montano, on which were found alphabetical engravings, the first and precious example of Greek writing to come to down us.

On the Phlegrean side, ancient signs of stable habitation dating to a period between the 7 and 6th centuries B.C., have been found in the Rione Terra, the old town of the present-day Pozzuoli. Rione Terra is a small volcanic promontory that at that time played host to a modest Cumaean mooring (see Fig. 1.24b). Between 529 and 528 B.C. some Samnite exiles, banned by the tyrant Polycrates, founded a colony on the promontory with the uncompromising name of *Dikaiarchia*, meaning 'Just Government', integrated into a territory still controlled from Cumae. In 194 B.C. the Romans transformed this small colony into a town called *Puteolis* (hereafter Pozzuoli), thus named for its abundance of thermal springs. The town soon became an imposing port and warehousing area for large quantities of foodstuffs. Before that, the Greeks moved eastwards, establishing the first inhabited elements of the city of Naples, between Mount Echia, an upland of volcanic origin, and the island of Megaride where the Castel Dell'Ovo (Fig. 3.5) stands today. The Greek migration from Ischia towards the coast was also influenced by the eruptions in the western and southern parts of the island that followed from the fifth century B.C. onwards. Amidst the lavas and the ash of the fifth century B.C. eruption and close to the port of Ischia, an old ground level was excavated containing potsherds and other archaeological finds from the 6 and 5th centuries B.C., demonstrating the existence of an ancient Greek settlement destroyed in the eruption. Again it was Strabo to bear witness to the eruptions in the Greco-Roman era, writing: "*……in ancient times a series of extraordinary events took place on the island of Pithecusae. […] when Mount Epomeo, which rises in the middle of the island, was shaken by earthquakes and erupted fire and (again) swept away everything that lay between itself and the shore and into the sea. At the same time a part of the ground, reduced to ash and thrown upwards, fell back onto the island*

Fig. 3.5 The Castel dell'Ovo, which rises on the islet of Megaride, a natural outlier of Monte Echia (photo S. Carlino)

like a maelstrom and the sea retreated for a distance of three stadia (about 500 m) *and, flowing back shortly afterward, flooded the island, extinguishing the fire. Such was the deafening noise that the inhabitants of the mainland fled from the coast to the inner regions of Campania.*"

The ancient city of Naples was called *Parthenope*, in honour of the enchanting mermaid who, according to myth, lies buried at the foot of the hill where the city sprang up. The site of Mount Echia, the current hill of Pizzofalcone (Fig. 3.6), was chosen for its defensibility, as the sea lapped the steep walls on three sides, while an ancient valley separated it from the hinterland. The towns of Naples and Pozzuoli, and the villages of the Vesuvius area, such as Pompeii, were expanding rapidly, knowing about the disasters of the Roman era, but rapidly having to deal with the adverse forces generated by the volcanic nature of the area.

After the eruption of Vesuvius that had devastated the north-western sector of the volcano during the Bronze Age (3800 years ago), for a short time this area remained sparsely populated. Many centuries later, as a result of the quiescence of the volcano and the expansion, firstly of the Greek colonies and then the Roman ones, the first coastal cities were born and spread out across the foothills of the volcano. Among these, the most important was certainly Pompeii. Because of its strategic position, the control of the city, initially a small centre, was contested by both the Greeks and the Etruscans before being invaded by the Samnites in the 5th century B.C. The process of the Romanization of Pompeii took place from 89 B.C.

Fig. 3.6 The site of Monte Echia, today Pizzofalcone hill, the first Greek settlement site in the current city of Naples

onwards, when the city was captured by Roman troops commanded by Lucius Cornelius Sulla. With the establishment of Roman rule and especially during the passage from the Republic to the Empire between 44 B.C. and 14 A.D, Campania not only became an important strategic and military site but an especially luxurious residence for aristocrats who liked to spend their leisure time there. The Latin, the term *otium* ("leisure") spending ones time in dedication to contemplation, reflection and studies, while its antonym, "*negotium*" or "not leisure", was understood as meaning work. Over time, the term has changed its meaning into a synonym for laziness, a label still sometimes applied to the Parthenopean people, but particularly the people from around the Campi Flegrei. Over the centuries their contemplation and reflective behaviour have turned into inertia, defining the character of a people who have inherited so much culture from the past but lie on the laurels of history without realizing their true value.

Campania was therefore at the centre of the interests of the Roman emperors, but not just to practice their *otium*. Trajan, for example, built a new Roman road, the via Traiana, as an extension of the oldest one, the Appian Way, connecting Brindisi to Benevento and opening a new communication route to the East. The Emperor Hadrian also granted many benefits and gifts to the towns of Campania, resurfacing and restoring roads and buildings, especially at Capua, the Emperor himself spending his old age at Baia (Fig. 3.7a, b) where he found a peaceful refuge in the last years of his life. Marcus Aurelius spent all the time managing the affairs of the Empire between Baia and Naples, only going rarely to Rome. The Roman Empire was also administered from Campania under the Severi dynasty, a tradition then interrupted by frequent military interventions along the borders of the Empire. Even when the crisis involving all the territories under Roman rule

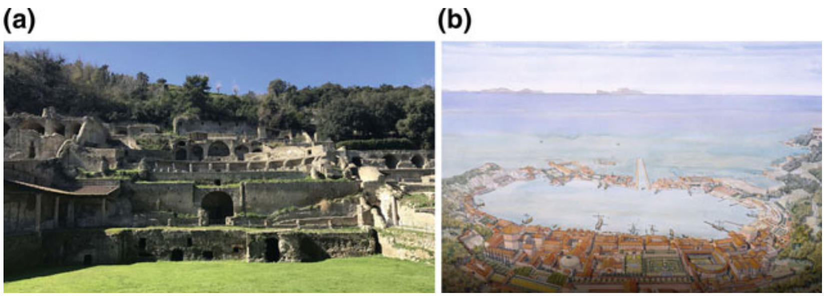


Fig. 3.7 **a** Baia was considered the best place to practice *otium* ('leisure') and one of the favourite places for this activity was the Roman Baths (photo S. Carlino). **b** Reconstruction of Baia in Roman times (Jean Claude Glovin)

reached its peak, Campania remained a very lively and active cultural centre. The economy of the region was mainly based on the production of foodstuffs, in particular wine, a drink sacred to the Romans, the grapes for which were nourished by the minerals provided by the Campanian volcanoes, the most important of all being the *vinum Falernum*, produced between the Monte Massico and the Campi Flegrei.

During the longest period of expansion of the Western Roman Empire, the cities around the volcanoes, laid out just a short distance from the eruptive centres of both Vesuvius and the Campi Flegrei, had expanded progressively. The volcanic activity of Ischia of the early centuries before Christ and its insular nature had, however contained its demographic expansion. The quiescence of the Campi Flegrei in eruptive terms had not meant that the volcanic nature of these places had been forgotten, the continuous puffs of steam and the hot thermal springs being a clear sign of that. But, in the minds of the people at least, the hostile nature of these places, sometimes sinister, was associated with the mood of the Gods, and not the actual nature of the area itself. In this emerges the vision of the natural disaster as a divine punishment for humankind and it was this vision that deceived the populations that lived below Mount Vesuvius prior to 79 A.D.

The volcano, which has been lying dormant for a few centuries, was considered a quiet one, although the descriptions of the observant geographer Strabo attributed its unusual appearance to "fire", writing "*Vesuvius is a mountain covered with fertile land, the summit of which it seems to have been cut off horizontally. The top is an almost flat and totally sterile plain, the colour of ash, in which one encounters, here and there, caverns filled with cracks, formed from blackened stones as if they had endured the effect of fire. Thus it can be assumed that there has been a volcano that has extinguished itself after consuming all of the flammable material that served to feed (the fire). Perhaps this is the cause to which we must attribute to the admirable fertility of the slopes of the mountain.*" Strabo's intuition is extraordinary, given the era in which he was writing. First of all, he gives us a first, albeit approximate, description of the volcano, from which one can perceive that its shape was different from what we observe today. It was probably made up of a single edifice, the ancient Monte Somma, slightly higher than the present one. Of the volcano, Strabone writes, that it seems to have had the top cut off horizontally, an observation that highlights the process of caldera formation that perhaps was already underway as a result of the explosive eruptions in the past. This description does not seem to coincide with the shape of the volcano in a fresco found in Pompeii, in the Centenary House (Fig. 3.8). The great geographer also recognizes the fertility of the soil as being due to the enrichment by minerals provided by the eruptions. However, the volcano was considered inactive and he

Fig. 3.8 A fresco of Vesuvius found in Pompeii in the Centenary House. The painting, as an artistic interpretation, probably does not accurately represent the real shape of the volcano, which was instead described by geographer Strabo as a mountain which had had its summit cut off horizontally (photo INGV Archive)

did not seem to contemplate the hypothesis of its possible awakening in the future. Vesuvius went on to produce signals that only later would be interpreted as possible precursors of the 79 A.D. eruption, such as the earthquake of 62 A.D. which caused fright and generated serious damage in the area around Vesuvius. After the 79 A.D. eruption, which caused the abandonment of the affected areas, the volcano was the source of a large new eruption in 472 A.D. during the decline of the Western Roman Empire. The two eruptions kept people at a distance from Mount Vesuvius, which had gradually changed its form due to the explosive events that had taken place.

With the arrival of the Visigoths and then the Vandals, and the subsequent barbarian invasions, the rule of the Western Roman Empire was over. In 476 A.D. the barbarian king Odoacer deposed the last emperor, Romolus Augustolus, who, because of his youth, was not executed but exiled to Naples, the last Roman stronghold of Campania. Of this great past, of Roman history and its splendour, there is still great testimony in Campania but this remained hidden until the beginning of the eighteenth century under the ash of Vesuvius and was brought to light with the archaeological excavations of Pompeii and Herculaneum. Thus the archaeological history that would one day make the Neapolitan volcano unique in the world had begun.

3.2 Pompeii, Herculaneum and the History of the Excavations

The ruins of Pompeii today bear witness that has no equal in the world. The urban fabrics of this city, its appearance and its characteristics have remained almost unaltered, with the streets still unchanged, together with the luxurious villas and wonderful frescoes. The peculiarity of Pompeii is precisely this, that it is not a city consumed and altered by time, nor an abandoned city in ruins and forgotten. Pompeii shows us its true face, the face of a city that belonged to another era, the life in which was abruptly and catastrophically interrupted, but which has maintained the characteristics and traces of its daily life. Pompeii is a window on the past, a snapshot of the Roman world, which leads us back to the dramatic moments of that August 24th 79 A.D., when, after a long period of quiescence, Vesuvius erupted, burying the city under few metres of incandescent ash (Fig. 3.9).

The first traces of the Roman cities buried by Vesuvius appeared as a result of works on wells and canals excavated to bring water to the increasingly populous cities of Campania. At the end of the 16th century, an aqueduct, bounded by the river Sarno to Torre Annunziata, crossed a hill called Civita, where Pompeii stands

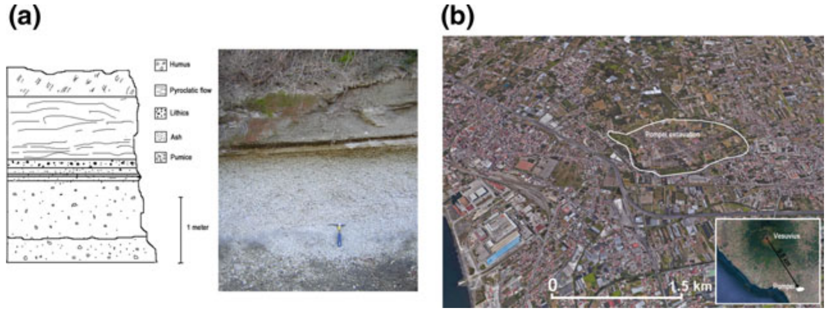


Fig. 3.9 **a** The stratigraphic sequence of pumice and pyroclastic flow deposits of the 79 A.D. eruption near Pompeii. One can observe the levels of pumice fall, produced during the formation of the eruptive column, and above these, the pyroclastic flow deposits generated by the collapse of the eruptive column (photo A. Fedele). **b** Indication of the Pompeii excavation area and distance travelled by the pyroclastic flows (9.8 km) during the eruption of 79 A.D. (from Google Earth)

today. The excavation brought to light the walls, tiles, fragments of tombstones and some coins but all material which was held in low esteem for its archaeological and historical value. In 1689, during the excavation of a well, some workers found a fragment of marble bearing the inscription *Pompei* with a large thickness of ash and pumice. This was attributed by scholars of the time to a villa belonging to Pompey the Great. Only in 1693 did Giuseppe Macrini recommence the excavations for himself near the well, recognizing walls and houses in ancient brick. The finds were illustrated in a book, *De Vesuvio* but did not provoke enough interest for a systematic excavation to be undertaken.

The Kingdom of Naples, governed since the beginning of the 16th century by Spanish viceroys, in the early 18th century had passed under Austria whose viceroy, the Prince of Elbeuf, who lived in Portici, is linked to the discovery in 1709 of the ancient Herculaneum, the other city buried in the eruption of 79 A.D., a discovery which also paved the way for the search for Pompeii.

In 1734 the kingdom of Naples and Sicily returned to the Bourbons of Spain and in Naples there arrived the eighteen-year-old Charles III of Bourbon. Charles bought the Portici villa from Elbeuf and, being fascinated by some finds from Herculaneum left behind in the villa, was tempted to resume excavations. However, it would appear that the eruption of Vesuvius of May 1737 terrorized him to such an extent that he remained closed for days in the *Reggia* of Naples, and later gave no further thought to archaeology.

With the arrival in Naples in 1738 of Maria Amalia Cristina of Poland, who became the wife of Charles III, the excavations were restarted at Herculaneum, under the direction of a colonel of the Bourbon Military Engineers, the Spaniard Roche Joachim de Alcubierre. An excavation method was established, involving vertical surveys, to the point where some traces of the building were found before then advancing with narrow horizontal tunnels. When crossing an ancient wall the diggers would generally overcome the obstacle by opening a hole. There are still some traces of these openings at different heights on the walls of Pompeii and Herculaneum and in the suburban villas.

While the recovery of Herculaneum had already been underway for a few years, Pompeii came back under scrutiny in 1745, when two Neapolitan scholars, Canon Alessio Mazzocchi and Abbot Giacomo Martorelli, discovered that a peasant working the land on the Civita hill had found other ruins. The two scholars were now certain, and they also convinced the King, that the ancient city of Pompeii lay on the site and when the Herculaneum surveys began to encounter areas with no finds, some workers were transferred to Civita site. Thus, in 1748 the exploration of the site of Pompeii began. The point chosen to begin the excavation fell right in the heart of the city, two hundred metres from the Temple of Fortuna Augusta and thus the number of excavators was rapidly increased. On 6th April the first beautiful frescoed wall was discovered and on 19th April the first human skeleton.

Meanwhile, during the excavations of Pompeii, attention again turned to Herculaneum, where, in September 1749, the wonderful Villa of the Papyri came to light. The finds at Herculaneum and Pompeii began to echo across Europe, and the mania for ruins and buried cities attracted entire royal families as well as men of science and culture to Naples, Vesuvius and the excavations. We are in the era of the Grand Tour, when the European aristocracy used to complete its cultural education with a trip through Italy, which included obligatory stops in Vesuvius and Pompeii.

At the end of 1754, during the construction of a road, the first tombs of the necropolis of Porta Herculaneum appeared and, only then, were some workers sent back to Pompeii. In 1759 Charles III left Naples to assume the throne of Spain, left vacant with the death of his brother. He was succeeded as ruler of the Kingdom of the Two Sicilies by the young Ferdinand IV. At that time Vesuvius was particularly active between 1755 and 1760 with effusive and strombolian eruptions.

In spite of everything, Charles III had shown great merit in excavating history. He pledged substantial funding to expand the excavation areas and considered every find as state-owned property. In addition to being the largest museum of antiquity in the world, the involvement of the public apparatus marked the rising of the science of archaeology and its passage from royal pastime to an affair of state.

In 1763 the excavation began of Porta Herculaneum and the funerary monuments around it. An inn also emerged with the skeleton of a mule still hitched to its cart as well as a large number of domestic utensils, plates, buckets, bottles, and five skeletons, four of which were found in a tight embrace. They thus began to outline the characteristics of an actual city. With considerable tenacity, Karl Jakob Weber, an engineer and archaeologist, who first explored Pompeii and Herculaneum, wanted to abandon the isolated surveys to proceed with a metre-by-metre excavations. He also fought to ensure that the painted walls, considered inadequate for the Royal Museum, were not demolished with picks and hammers.

When, in August 1763, a statue came to light with the inscription "*in the name of Emperor Caesar Vespasian Augustus, the tribune Titus Suedius Clemens has returned to the city of the Pompeians the lands belonging to the community….*" the final sceptics were convinced that the city of Pompeii lay beneath the hill of Civita. Towards mid-1764 Sir William Hamilton arrived in Naples as British ambassador. Passionate about art and politics, intelligent and aristocratic, he followed the excavations with a passion and was also a careful observer of the volcanic activity of Vesuvius. Towards the end of 1767, Hamilton described the eruption of Vesuvius which forced the King to move from Portici to the palace of Naples (Fig. 3.10). On 12th January, 1767 the King came of age and, in April 1768, married the Archduchess of Austria, Caroline, the daughter of Mary Teresa. His marriage, like that of his father, was to prove decisive for the fate of the excavations. Caroline devoted time and enthusiasm to the excavations of Pompeii, which in that period were proceeding around the Theatre, the Odeon, and along the

Fig. 3.10 The Vesuvius eruption of October 1767 (Engraving, Unknown Author)

via Sepulchre. As a result of support from her brother, the Emperor Joseph of Habsburg, who exhibited a true passion for Pompeii and tried to convey it to the King, the excavations were redoubled with an increase in the workforce.

In 1775, the Minister Tanucci decided to proceed with the excavations in an orderly fashion from Porta Herculaneum to the heart of the city, putting an end to the search that served only to enrich the royal art collections. From a mere personal interest, with time the excavations became the incentive to study and revisit Roman history and the events that saw the destruction of Pompeii and Herculaneum by Vesuvius.

However, the excavation operations were slowed down as it was decided to no longer re-bury the buildings and thus it took a long time to clear the overburden. Breaks in the work were also caused by the eruptions of Vesuvius, which at that time was in almost continuous activity, that had begun in 1631. In addition to the eruptions, such as those of 1779 and 1794, the events at the end of the century, with the French Revolution and decapitation of Marie Antoniette, Caroline's sister, the archaeological explorations were interrupted. The arrival of the French in 1798 provoked the precipitous escape of Ferdinand and Caroline to Palermo. The French general Championnet proclaimed the Parthenopean Republic and, having restored order, resumed the excavations of Pompeii. The French left Naples in 1799, but the Bourbons did not return from Sicily until a few years later. In 1804 the management of the excavation of Pompeii was entrusted to Pietro La Vega, the brother of Francesco, who maintained it for ten years.

After various events, when Napoleon conquered Spain, Giuseppe Bonaparte had to leave Naples to assume the Spanish crown and from July 1808 he was replaced by Joachim Murat. Once again, it was Murat's wife, Caroline, Napoleon's sister, to show an interest in Pompeii. With enthusiasm she had the digging re-started at full speed, taking on over 1500 people for the excavation work.

To keep the attention of the royals focussed on Pompeii and Herculaneum (the funding for the excavations depended on them) it had become customary during the visit of famous guests to have the diggers "discover" skeletons and gold objects previously laid out and covered with pumice and it was with these tricks, which certainly entertained visitors, that Caroline became an accomplice to the excavations and pushed her husband to allocate more funds.

The excavations at Pompeii underwent a slowdown once again with the return to Naples of the Bourbons, sanctioned by the Vienna Congress. Ferdinand, left alone after Caroline's death in exile, to whom the debt was owed of publicizing the excavations with correspondence and printing guides and maps, did not make any further money available. After a situation of almost total stasis, the Austrian general, Baron Franz von Koller, resumed the excavations, without neglecting to create a private collection of ancient vessels for himself, acquired in 1828 by the Berlin Museum.

In 1822 an eruption of Vesuvius covered Pompeii in a thin mantle of ash. The eruption formed a large crater and lowered the volcano by about 90 m. In 1824, the Temple of Fortuna Augusta and the Thermal Baths of the Forum were excavated, where round glass windows and 778 oil lamps were found, showing the night-time attendance at the baths. In 1831, in the House of the Faun, a beautiful mosaic was freed from the pumice which, consisting of tiny polychrome tiles and depicting the battle between Darius III of Persia and Alexander the Great. The mosaic exhibited remarkable traces of restoration, probably as a result of damage sustained during the earthquake of 62 A.D. It took months of work to remove the mosaic from the floor and then transport it to the Archaeological Museum of Naples. Despite the finds being more and more surprising, the interest of the sovereign was scarce and the work sporadic. With the riots of 1848, which sought to regain the constitution that Ferdinand's father had quickly abolished, Pompeii was abandoned. In 1850, the excavators returned to work at the Stabian Thermal Baths and at Porta Stabia, outside the perimeter of the walls but the uncovering of the buildings to accumulate finds for the Naples museum continued to demolish Pompeii more than the eruptions had done.

Following the Unification of Italy, Giuseppe Garibaldi entrusted the management of the museum and excavations to the famous French writer Alexander Dumas, who had supported him in the Expedition of the Thousand. Isolated from the Italian environment, Dumas quickly left the position that he had accepted with great enthusiasm.

After passing of the regal baton to the House of Savoy, King Vittorio Emanuele II resumed excavations with a substantial amount of money. To this he added a director who marked a turning point in the history of Pompeii, the archaeologist Giuseppe Fiorelli. With Fiorelli, the excavation criteria changed radically. Despite the various attempts to unify the urban environment, so far, individual buildings had been uncovered, accumulating material between them and creating a landscape of hills and valleys. In addition, the paintings exposed to the weather had deteriorated and the open environments were quickly swallowed by scrub.

The work began again from the already-uncovered streets and, to avoid collapses, the houses were entered from above. The resulting material was cleared by wagons running on rails like those found in mines. The wall paintings were protected and left in place, the houses covered with roofs and the buildings connected to each other. The town was divided into districts and these in turn, into blocks.

At that time, in 1864, a brilliant piece of intuition came to the archaeologist Fiorelli. Looking at a cavity formed in the ash layer, he saw the skull of a man. He had the idea of filling the void with plaster-of-Paris, a material already used to make moulds of coins. Once hardened and cleaned of the ash, the chalk revealed the shape of four bodies, with the clothes, jewellery and even the contracted expression of the face being faithfully reproduced. The ingenious expedient of plaster casts was thus applied to the bodies of humans and animals and even to those materials that had been consumed, leaving their cast in ash, such as doors, furniture, and trees. Objects that were barely included in the inventory of finds became as important as jewels and statues. As a result of the efforts in Pompeii and Herculaneum, archaeology began to emerge as a science, and soon archaeologists and volcanologists were working together in an attempt to reconstruct the various phases of the 79 A.D. eruption at the two sites which were now famous all over Europe (Figs. 3.11, 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, and 3.20).

Fig. 3.11 The house of Obellius Firmus, Regio XI, Insula 14, with the discovery of five skeletons during the excavations at the end of the 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

Fig. 3.12 House of the Chaste Lovers, Regio IX, Insula 12, with the discovery of two skeletons during the excavations at the end of the 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

Between 1880 and 1881 the southern area of Pompeii were excavated, where the Sarno had once entered the sea, before the eruption deposits had changed its course and many skeletons were found of people carrying precious objects who had died while trying to escape the fury of the volcano.

Vesuvius became active again with a violent eruption in 1906. At that time the management of the work was entrusted to Antonio Sogliano, after whom Vittorio Spinazzola took over until 1923. This Neapolitan scholar was responsible for the resumption of works on a large scale along Via dell'Abbondanza, connecting the Forum to the Amphitheatre. On the walls of the main route through Pompeii, the discovery of various writings opened up a view on the public and private traditions of the people of Pompeii.

The work, suspended for duration of the war in 1915, resumed in 1924 under the oversight of the great archaeologist Amedeo Maiuri, a figure who proved decisive both in the excavations and in the publicising of the results. The genius of

Fig. 3.13 Regio IX, Insula 11, amphorae immersed in the cineritic flow deposits during excavations at the end of the 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

the new manager was added to the longevity of his tenure which lasted for over 30 years, despite the scepticism with which he had been welcomed after a period of centralised administration. Having received the directive to preserve, restore and re-order the site without new excavations, the archaeologist firstly re-evaluated what had already been brought to light, starting from the houses in the via dell'Abbondanza of which only the facades had been freed from the ash before moving on to actual excavations in the house of the priest Amandus. During these new excavations the remains of nine people were found who had crowded into it in an attempt to reach the road. Maiuri devoted particular care to the composition of an evolutionary picture of the city, studying the changes made in the buildings, from the ancient Italic village through to the monumental houses of Roman times. Discoveries were regularly published and featured beautiful illustrations.

Fig. 3.14 Great Gym, Regio II, Insula 7, broken columns at the top of the pumice deposits found during excavations at the end of the 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

Fig. 3.15 Palestra Grande, Regio II, Insula 7. Excavations from the late 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

Fig. 3.16 House of Loreius Tiburtinus, Regio II, Insula 2. Excavations of the late 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

The excavations in Pompeii, which had survived almost two centuries of battles and changes of hand were not spared by the Second World War. In order to prepare for the disembarkation of troops, on 24th August 1943, allied aviation bombed Pompeii, suspecting that German units were hiding amidst the ruins. A bomb fell into the Forum and another on the small museum at the entrance to the town where the chalk casts made by Fiorelli were preserved.

Maiuri wrote letters and tried in a thousand ways to save Pompeii from a second destruction. He also turned to the great philosopher and historian Benedetto Croce, believing that such an authoritative voice could stop the bombing. After 8th September (and the Armistice of Cassibile signed between the Allied Powers and Italy), the bombing resumed with vigour although the damage was less serious than expected. Maiuri was forced to abandon the excavations on a bicycle and was even injured during the escape. In 1944, during the last eruption, Vesuvius had its revenge, however, and covered an entire squadron of American bombers parked at an airfield near Pompeii with ash, damaging them irreparably.

Fig. 3.17 House of Menander, Regio I, Insula 10, the discovery of two skeletons in a sheltered position. Excavations of the late 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

The post-war reconstruction also indirectly involved Pompeii. Since 1951, Maiuri had financed the excavations by selling the pumice to the repair works underway on the Naples-Salerno motorway. Removing the old heaps, to maintain the works, the excavations were concentrated in the areas with more overburden, such as gardens and open spaces, neglecting the closed environments. In the decade 1951–1961 about one million cubic metres of material were removed. The work went so fast that it did not leave time for restoration work and even the registers covering those years were rough and ready and remained unpublished.

The post-war public administration showed little consideration for the protection of Pompeii. The degradation of the old excavations, the expansion of development, the lack of proper laws and funds almost brought the excavations of Pompei to the brink of the collapse. Since 1962, interventions have been mainly aimed at conservation, while new excavations became less important. In 1976 a

Fig. 3.18 House of Cicero, Regio I, Insula 8. Excavations from the late 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

special law was passed to stop the degradation of the artefacts and to cope with the growing number of visitors. Since the 1980s, many works, such as the completion of the excavation of the House of Julius Polybius, will finally have a contribution from volcanologists. With the development of quantum volcanology and volcanic modelling, and following the observation of explosive eruptions in different parts of the world, Pompeii and Herculaneum have become an open-air laboratory for the study of volcanic processes. The stratification of the deposits, analyses of damage to buildings, the study of casts and skeletons, combined with descriptions of the moments of the eruption of 79 A.D. in the letters of Pliny the Younger, are allowing volcanologists to define the energy of the event, to establish its effects on buildings and people and to quantify its duration. For the first time in history, they have an enormous amount of information about a past volcanic event which certainly left its mark on Roman civilization, and even further afield.

Fig. 3.19 House of the Ephebe, Regio I, Insula 6, restoration of a statue in the level of pumice. Excavations from the late 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

The history of excavations also appears as a chronicle of terrible errors, but it is necessary to frame the events in the historical context in which they took place for an objective analysis of what has gone on in Pompeii and Herculaneum for the past 300 years. Generations of archaeologists have dealt with digging and restoration work in the light of their own cultural baggage, situating themselves in a varying ways when faced with the problem of restoration and enhancement of the work. The passage from a search aimed at simple collection of ancient pieces through to research, accompanied by restoration, enhancement and historical interpretation, has certainly been a major achievement and provided a fundamental impetus to archaeological research.

Today, however, the problem is one of managing an immense archaeological and cultural heritage, which time will inevitably tend to consume, and which the volcano itself, possibly one day, will again cover in ash.

Fig. 3.20 *Domus Paqui Proculi*, Regio I, Insula 6, falls of tiles in the pumice layer. Excavations from the late 19th century (Pompeii) (Archaeological Superintendence of Pompeii)

3.2.1 Herculaneum

Ancient Herculaneum stood facing the sea and was equipped with a small harbour, lying on either side of two streams. Herculaneum, as it emerged from the excavations, unlike Pompeii, seems to resemble a quieter and less hedonistic town, largely given over to fishing and seafaring. This is shown by large quantities of nets, hooks, ropes and mariners' equipment together with some boats that were found (Fig. 3.21).

Even the decorations and the architecture of the houses found during the excavations gave the impression of Herculaneum being a city in which some of the features seemed more noble and refined. Homes in Herculaneum sometimes appear more evolved in their forms and typologies than those in Pompeii, with a prevalence of private constructions and many mercantile and rented houses in the town had undergone modernization, especially after the 62 A.D. earthquake, gaining space in height with the development of upper floors. It is likely that this process of

Fig. 3.21 The archaeological excavations in Herculaneum. In the background the crater of Vesuvius (photo S.Carlino)

modernization was more evident in Herculaneum given its proximity to the city of *Neapolis*, which certainly exerted a strong influence on the development of the towns to the west of Vesuvius. Herculaneum suffered less from the influence of trade and industry than Pompeii and for this reason, the contrast between the noble and ordinary homes appears deeper and more profound. Many of the most luxurious villas were built to enjoy the panorama out to sea, along the south-facing belvedere.

During excavations, a large number of wooden artefacts were found, a characteristic of Herculaneum, with valuable antique furniture, wardrobes and cribs, as well as machinery for workshops and small shops such as presses, winches and looms. Even the frescoes and decorative painting are more accurate and refined than those of Pompeii. For this reason, the excavations of Herculaneum are able to infuse the visitor with greater emotion, in an attempt to re-evoke the life lived before the 79 A.D. eruption. Among the most beautiful buildings, the Theatre stands out. It could accommodate up to 3000 spectators on 10 rows of steps. Other fine buildings include the House of Argus, whose nobility passed through the beautiful peristyle with stuccoed columns, the *Casa dei Cervi* (the House of the Deer), with a bright garden and large rooms with polychrome flooring, a shop with furnishings still on the sales counter as well as carbonized cereals and legumes, a wooden loft onto which the amphorae were loaded and unloaded, the Samnitic House dating back to the pre-Roman Age, with its pretty loggia, columns and finely stuccoed screens.

Among the most beautiful finds made at Herculaneum, the Villa of the Papyri certainly has to have its place. Located in the suburb northwest of the city, the villa was investigated using tunnels between 1750 and 1761 but only in part. It was then revealed in all its glory with excavations that lasted between 1996 and 1998 and coordinated by Antonio De Simone. The Villa of the Papyri covers an impressive area for about 250 m parallel to the coast and consists of a residential quarter, a long garden and a pool with a belvedere. The columns of the peristyle extend for 100 m in length and 37 m in width, while the swimming-pool is 66 m long. The name of the Villa comes from the discovery of about two thousand charred *papyri*, written mostly in Greek. Some of these were unrolled and deciphered, providing epicurean texts in Greek. The *papyri* are now kept in the National Library of Naples at the International Centre for the Study of the *Papyri* from Herculaneum. In addition to the *papyri*, excavations have brought to light splendid mosaic floors, fragments of frescoes and various marble and bronze sculptures, now preserved in the Archaeological Museum of Naples.

3.3 Volcanoes and Harbours

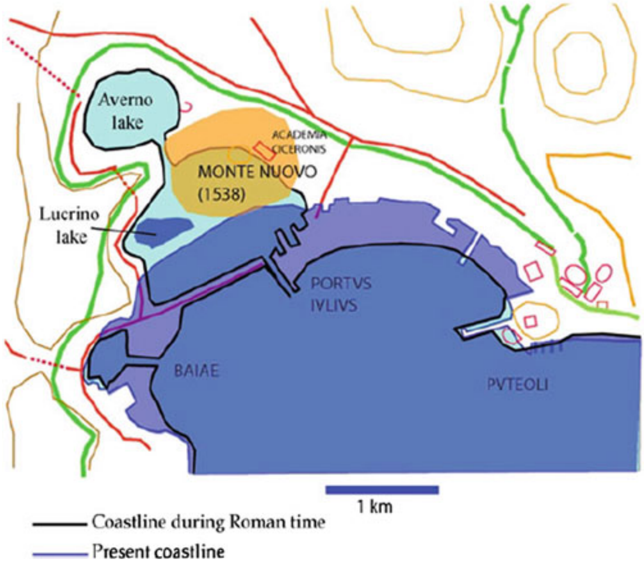
3.3.1 Portus Julius in the Campi Flegrei

When the populations that had settled in the volcanic areas around *Neapolis* had begun to occupy the territory more extensively, the natural spaces were gradually modified by anthropic activity during the construction of new infrastructures. The nature and morphology of the volcanic coasts, jagged and rich in creeks, represented a shelter for the first navigators, initially for the Greeks and then for the Romans. The latter were the first to use the natural lacustrine inlets to create large ports for their naval fleets. The *Portus Julius*, rediscovered in 1956 and now submerged about 3–5 m below the wave in Pozzuoli Bay, is one of the most important archaeological finds in the Campi Flegrei. Between 38 and 36 B.C., during the war against Sextus Pompey under the Emperor Octavian, the admiral and architect Marcus Vipsanius Agrippa was commissioned to build a new naval base in the Averno-Lucrino lake complex. The great new port was called *Portus Julius* in honour of Caesar. With the help of architect Lucius Cocceius Auctus, the harbour was created by removing a sandy strip dividing Lake Lucrino from the sea and digging a waterway between this lake and the Averno (Fig. 3.22). The Lucrino, once broader than the present lake, was a real harbour for mooring ships, while the Averno served as a shipyard for taking ships requiring a haven. A 372 metre-long coastal jetty was built to protect against tidal surges and constructed on arches lying on fifteen quadrangular pylons. The harbour was defended by a long embankment along which passed the Via *Herculea* which included the entrance to the navigable canal that led to the Lucrino (Fig. 3.23). The military complex was completed with underground walkways commissioned by Agrippa to put the Lake of Averno in secure communication with the port of Cuma.

Soon the new port infrastructure had to deal with the phenomenon of the bradyseism of the Campi Flegrei. It would seem, in fact, that the military function of the harbour ceased about twenty years after its construction due the phenomenon of partial silting-up with the Roman fleet being transferred to the nearby port of Miseno in 12 B.C. where the deformations of the ground were less intense. At that time the entire area was subject to a sinking trend of the ground at a rate of about 1–2 cm per year. However, we do not know if this trend was interrupted by short lifting phases. If we consider the sinking rate over about twenty years the port structure would have dropped by 20–40 cm. This would have made the barrier protection against tidal surges less effective but it is also likely that changes in the local currents as a result of the continuous lowering of the ground brought about a greater contribution of sediments, both from the coastal area and the sea itself, causing silting phenomena. For a long time, until the 4th century, *Portus Julius* retained its commercial port function. In the Augustan era the port settlement prospered considerably, extending as far as Pozzuoli with the construction of new suburbs. In the following centuries, the retreat of the sea coast, due to bradyseism, brought about the complete submerging of *Portus Julius,* also demonstrating that the Caldera of the Campi Flegrei has undergone changes in sea level over the course of millennia due to magmatic upthrust and sinking due to its subsidence. The action of magmatic upthrust would have been more active in the onshore area along the La Starza marine terrace, lifting a rising block, while the subsidence, at least over the last 2000 years, has prevailed in the offshore zone, and close to the coast.

Despite the problems encountered in the operation of the harbour, under Nero the Romans undertook the construction of a very long navigable canal, the


Averno lake
Monte
Nuovo
Campi Flegrei
Lucrino lake


Averno
lake
ACADEMIA
CICERONIS
MONTE NUOVO
(1538)
Lucrino
lake
PORTVS
IVLIVS
BAIAE
PVTEOLI
1 km
Coastline during Roman time
Present coastline

◀ **Fig. 3.22** The Campi Flegrei Caldera - Averno and Lucrine lakes and Monte Nuovo tuff cone (1538) as they appear at the present time (figure above). During Roman times (figure below) the isthmus which separated the two lakes was removed in order to obtain a channel for the passageway of the Roman fleet (*Portus Iilius*). The products of the Monte Nuovo eruption covered a large part of Lucrine lake. The submerged archaeological ruins indicate that the ground level is lower than the Roman time one. This is due to the prevalence subsidence occurred in the last 2,000 years in the offshore area (after Pappalardo 2006 and Carlino et al. 2011)

Fig. 3.23 The ruins of the submerged Roman port along the Lucrine coast (photo: C. Tripodi)

so-called *fossa Neronis*, which was to have connected *Portus Julius* to Ostia (on the Roman coast), to allow safe traffic during storms for the commercial vessels that supplied the capital. The construction of the canal was interrupted by the death of Nero without ever being completed. The total length of the waterway should therefore have been 236 km, with a maximum width of about 60 m. In fact, net of lakes and coastal lagoons to be incorporated in the route, the excavation would have probably required less work than this with diggings accounting for about half of the total length. In addition, the canal, in spite of the planned excavations, would have followed a very broken route, making it difficult to overcome the adverse mountain ranges mentioned by Tacitus, being blocked by the irregularities along the coast such as the Itri gorge, the *saxa Formiana* and the the cliff at Terracina. It was, however, a project on a gigantic scale, far greater to any other up until then, including the drainage of Lake Fucino under Claudius which used 30,000 men for a period of eleven years.

In the Renaissance period, due to the eruption of 1538 that formed the volcanic edifice of Monte Nuovo, there was a considerable lifting of about 20 m in the area with the reconstitution of the lake basin of Lucrino even though this was less extensive than the ancient one, and, with the definitive closure of the connecting channel between Lake Averno and Lake Lucrino (Fig. 3.24).

Fig. 3.24 Detail of the Lake of Averno. The ancient channel of communication between Averno and Lake Lucrino has undergone continuous upheaval, following the bradyseism, definitively separating the two lakes (photo A. Fedele)

3.3.2 The Bourbon Kingdom and the Public Works: The Example of Ischia Harbour

The opening of Ischia Harbour occurred in a period that saw the considerable reforming impetus in public works throughout the Bourbon kingdom in southern Italy, especially in the region of Campania. This climate of reform started under the Spanish viceroy in 1610 when the first major intervention was launched in the region, the construction of a channel across the Campanian Plain north of Naples, the so-called *Regi Lagni* (Fig. 3.25), the aim of which was to avoid the recurrent floods tormenting the local people that had been preventing urban growth since pre-Roman times.

As often happens in the history of great monarchies, in southern Italy both during the Bourbon and French dominations (1737–1860), the sovereigns used to prove their greatness and benevolence by carrying out public works on a "grand scale", at the same time providing essential contributions for regional change and improvement. Modern macro-engineering endeavours are the equivalent of these works on a "grand scale" in olden times. The city of Naples and its surrounding

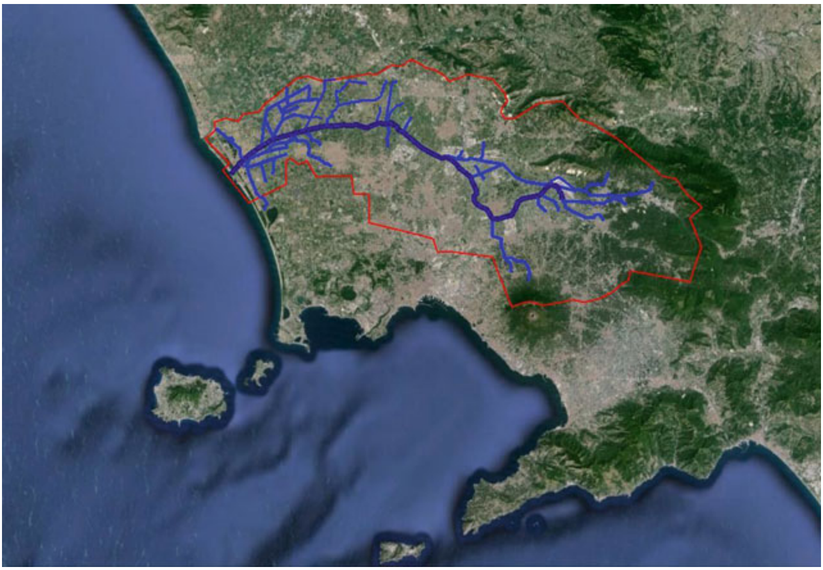


Fig. 3.25 The water management basin (red line) of the Regi Lagni. The main and secondary canals are shown in blue and were made during the Bourbon era with the aim of mitigating the effects of flooding in this area

areas played their part in such modernizing change. This active involvement would ultimately lead to the founding of the Naples school of engineering, via a decree dated 18th November 1808, upon the initiative of Joachim Murat, which established the Engineers Corps for Bridges and Roads. Thus arose the imposing figure of the omnipotent overseer, the State engineer, whose career was mostly based on meritocratic choice in the interests of more rational land use.

With the arrival of the Bourbon Ferdinand II in 1830, the city of Naples and its surrounding areas experienced a period of considerable economic development, lending it a modern, advanced image (Fig. 3.26). In this period the first gas-lights were installed on the streets of Naples, roads and communication networks in general were improved and built *ex novo*. In 1839 the first railway line established in Italy was built, connecting the city of Naples with the town of Portici situated on the slopes of Vesuvius. The island of Ischia was also included in this vast programme of public works. One of these projects included Ischia harbour, which was derived from the opening of an ancient crater lake towards the sea. The crater of Ischia Harbour was formed several centuries B.C. by a phreatomagmatic eruption, during which the explosive energy increased, followed by a magmatic phase with

Fig. 3.26 Map of the city of Naples in 1800 (John Stockdale)

strombolian activity (Fig. 3.27). The volcanic products in the eastern sector overlie a palaeosol developed on top of an older trachyte containing pottery remains from the 5th century B.C. together with roof tiles from the 6 to 5th centuries B.C.

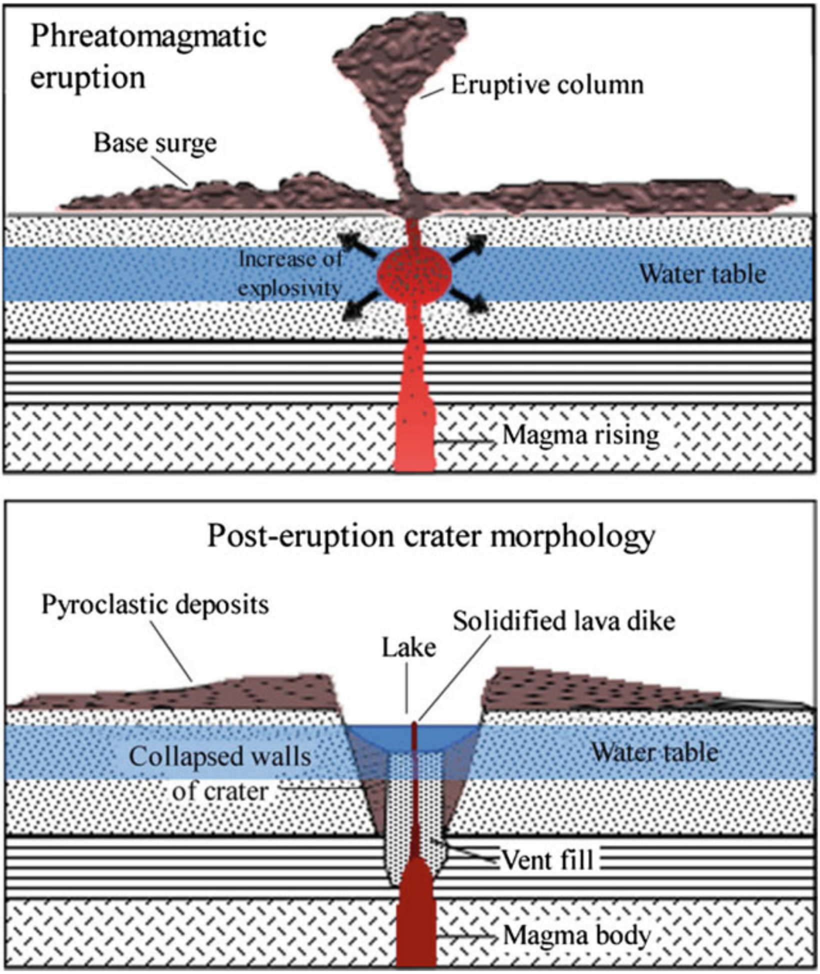


Fig. 3.27 Sketch of the formation of the crater-like Ischia Harbour (maar-type). This was formed after small phreatic eruptions during which the magma comes into contact with water and increases its explosivity (see above figure). After the eruption a moderate collapse of the crater occurs, while the lava which has feed the eruption solidifies forming a dyke, the volcanic depression being refilled by the water (figure below) (after, Carlino et al., 2011)

Ferdinand II was personally very fond of the island of Ischia. Together with his second wife, Maria Theresa, and their many offspring, he spent several months there every year, relaxing by the Lago dei Bagni, in the Royal Lodge that dominated its shoreline from the hill nearby. When the King arrived, he said: "…*of the lake we shall make a harbour, it will be the lifeblood of Ischia*". As often happened during the Bourbon period, the vacation macro-project idea swiftly became reality. Its purpose was twofold: to increase the consensus for Bourbon initiatives to renew the kingdom and transfer their own representative on the island from the castle to these delightful, unspoilt places. This was the necessary step to carry out the "Royal Delights" project which the same Ferdinand II completed with the conversion of the Buonocore residence into a Royal Lodge, with the construction of the Church of Portosalvo and the restoration of the royal space adjacent to the entire area of the future port.

The Provincial Council of Naples turned down the planning application from the Council Authority of Ischia to build the harbour, since the intervention was not deemed useful and the island was not viewed as a priority for development. On 13th March 1853 the far-sighted King Ferdinand II, convinced of the importance of the work, overrode the decision and passed a decree to transform the lake into a harbour for Ischia. Although the initial budget estimate was 50,000 ducats, modifications to the project when it was under way saw the costs climb to over 126,000 ducats, a considerable sum at that time. By 25th July of the same year the works had already begun, and were completed in only 14 months, a relatively short period for such a construction given the resources and the technology available at the time (Fig. 3.28).

From the preliminary analysis of the lake's characteristics, commissioned by the king, we have the first information on the nature and economic scale of the works to be undertaken. The latter involved the removal of part of the sandbank separating the lake from the sea to the north, with an entrance of 500 palms (130 m). A jetty was also to be constructed to protect the harbour mouth from the strong NNW winter winds, about 700 palms (182 m) long and consisting of about 541 cubic *canne* (10,000 m^3) of rock obtained from a cliff beyond the small river mouth to the west, and the bed was to be dredged to allow access for large vessels as well. The entire lake-bed was excavated, removing material about a metre deep and amounting to 115,000 m^3. To enable these operations, on 31st May 1854 the King commanded a small, specialised fleet to be transferred to the project, consisting of two steam dredgers, a small steamship, and a four-boat tug to protect the harbour entrance. In addition, an ancient water/debris collection tank situated near the Buonocore residence that was blocked was to be emptied so as to prevent

Fig. 3.28 The gouache by F. Mancini (1853) reproducing the works during the opening of the isthmus separating the lake from the sea (Private Coll.) (From Caputo 2000)

storm-related flooding caused by streams to the south invading the lake-bed, making safe navigation more difficult.

The macro-project for constructing the harbour was assigned to the Inspector of Bridges and Roads Luigi Oberty and Lieutenant Domenico Milo of the Engineering Corps, while the project director was Camillo Quaranta, a commissioner of the Royal Navy. The latter left behind copious documentation regarding the state of the works, which point out the difficulties encountered during the work, the mishaps and some technical details on intervention topologies. Before embarking on the sand removal works, Quaranta first strengthened the lake shores with walls supported on robust iron frames. He then built further embankments to flank the short channel entrance opening to the sea and raised the quay for moorings. The cutting and removal of the sand bank to open up the channel to the sea was completed 4 months later. King Ferdinand II was never present during these operations, but waited for the work to be completed, on 31st July 1854, before entering for the very first time aboard the Royal Steamship *Il Delfino*. It was a sort of technical test and verification of the works prior to the official inauguration held on 17th September. The news was reported in the *Giornale delle Due Sicilie* as an event of worldwide importance and enthusiastically fêted by the entire population of the island. The inauguration took place amidst the boom of discharging artillery, the lyrical notes of several musical bands, the enthusiastic sounds of the excited throng of happy islanders decked out in party costumes and about 200 ships and boats. The parade of vessels was preceded by the Royal launch, followed by the warships *Tancredi*, *Saetta*, *Delfino* and *Antilope*. Thus began a new era for Ischia, in which the harbour played a key role in changing both the island itself and relations between the island and the mainland.

Works to improve the structure of the harbour continued for about 2 years. At the end of the protective breakwater, on 15th December 1856 a fifth-order lighthouse was lit for first time. For ships arriving from the northeast, the Ischia Harbour lighthouse, together with the smaller warning light from the nearby island of Procida, represented an important reference point for coastal navigation in the channel that separated the two islands from the Italian mainland. Towards the south, on the other hand, the Ischia lighthouse with that of Capri, about 21 miles further south, was to prove very useful for large vessels sailing to and from the islands of Sicily and Malta. Works to redesign the harbour area were completed with the construction of the church of Santa Maria di Portosalvo in 1856, crowning the programme of Ferdinand II of the Royal Delights of Ischia in the last few years of his reign.

Ischia Harbour, therefore, played a fundamental role in opening up the island towards the sea and the mainland, allowing new trading and cultural links, increasing spa and recreational tourism still further and supplying a new structure to the island in which the harbour became the pivot for the island's social and demographic growth.

From 1943 to 1945 the harbour played a role of vital importance as an Allied naval base in the Mediterranean basin, taking its cue from what was happening on the mainland in the regions of Campania and Lazio, a few miles away. In the years after the Second World War Ischia harbour retained all its splendour. However, the subsequent post-war economic boom and increase in tourism were to change the area progressively, resulting in excessive population pressure. This was to lead to a gradual covering and a sealing of the natural landscape by a distinctly transformed and man-made landscape (Fig. 3.29). However, the volcanic structure of this area is still predominant and its natural evolution must be taken into account when assessing the island's future economic and demographic development scenarios. Today, Ischia harbour is deep enough to accommodate the navigation of rather large motorized and sail-driven ships.

Fig. 3.29 The port of Ischia, today the main seaport on the island (photo: A. Fedele)

3.4 The Eruption of Vesuvius in 1631: Naples and Its Punishments

It cannot be said that the first half of the 17th century was a good period for Naples. The eruption of Vesuvius in 1631, the most catastrophic in recent times, occurred in a historic moment in which Naples had been plunged into a serious socio-economic crisis, weighed down by its subjection to the crown of Spain which, fighting increasingly expensive wars, demanded heavy taxes from the Neapolitans. In 1647, the miserable conditions in which the people found themselves brought about an insurrection, with a revolt led by Masaniello, who, for the Neapolitans went on to become one of the symbolic figures of the rebellion against the abuses of the nobility and the *bourgeoisie*. Less than ten years had passed when Naples had to face one of the most unfortunate moments in its history, with a epidemic of the Plague that exploded in 1656 and caused over 200,000 deaths in a population of 450,000. Calamitous events to which a theological meaning was attributed, as an expiation of punishments and in this sense the eruption of 1631 represented a symbolic event, which in the coming centuries affected not only volcanology, but also other political, sociological, literary, and above all, religious disciplines. In the 17th century religion was still the main cause of controversy and wars, while scientific thought had taken its first steps shortly thereafter, thanks to Galileo Galilei. With the Council of Trent (1465–1563) an attempt was made to repress the intellectual research of the Renaissance, with the strengthening of the

Orthodox beliefs and the "truths" of the Catholic Church, which had prevailed during the Middle Ages. In 1631 the Counter-Reformation was in full swing in southern Europe, when Naples was dominated by the Spaniards. In Spain and its dominions, the fervent servants of the Church, reinvigorated by recent events, sought to ensure the unconditional acceptance of this "truth" across all aspects of life on Earth and that the Almighty had revealed to his representative in Rome. The predominance of religious thought over the rational one was also guaranteed by the Inquisition, which fought assiduously to try to condemn heretics who contested these truths. In Naples, the only salvation in this prevailing climate was that the Inquisition was never allowed to cross its threshold. However, the church exalted many dramatic, natural and social aspects, such as the disasters that frequently befell people, to show that these were nothing but the divine will, so as to reduce people to obedience to an angry God. This was the prevailing thought, which lasted in Europe until 1755, when another disaster, this time in Portugal, triggered a new philosophical debate on the meaning of such calamities. This was the devastating earthquake that struck the city of Lisbon, and that fate had wanted it happen on All Saints Day, Saturday 1st November and in the capital of a strongly Catholic country with a long history of Christianisation and evangelisation. But at that time philosophical thought was radically changing through the Enlightenment whose thinkers debated the so-called "philosophy of catastrophe". For the Vesuvian eruption of 1631 the cause of such a calamity was therefore attributed to the sin of the people and the expiation of divine punishments. Only repentance could calm the divine rage, and forgiveness was all the more guaranteed the more public and theatrical the repentance engaged in. The significance of the religious processions that often accompanied the eruptions of Vesuvius volcano lay in this, and what better occasion than the catastrophic eruption of 1631 to reaffirm the orthodox doctrines? The Counter-Reformation had laid a heavy hand on scientific research, so much so as to make a rational explanation difficult for the eruption of Vesuvius, a fact that also involved an irrational response of the population in the organisation of relief efforts. Joining the processions of the flagellants was the way to manage a crisis according to the most fundamentalist religious thought.

The events of 1631 also provide a worry increased in the followingision of the volcanological controversies that arise from the lack of knowledge of the phenomenon and the incorrect interpretation of a natural catastrophe. The eruption gave rise to hundreds of written accounts, in many cases exhibiting a Renaissance attitude towards natural phenomena. However, this happened after almost 500 years of volcano quiescence, so even the most attentive observers of the phenomenon had never actually seen an eruption and they did not yet know how to analyse the scientific aspects. Nor did they have a defined terminology to describe what was happening in a coherent fashion. The term volcano itself was not in common use, just as the term lava (in its volcanological sense) would only enter common usage in the following century. For these reasons, the events of 1631 were often badly interpreted, so much so that it had long been believed that, unusually, it was the lava flows (and not the pyroclastic flows) that, at least in part, caused the devastation of the cities located at the foot of Vesuvius. The confusion also originated from the term “lava”, which at the beginning was used to represent the mud flows, which had also been one of the main causes of the damage of the 1631 eruption.

From an analysis of the cultural context of the Era, what emerges from the event is the predominant role of the Italian religious hierarchy and the Spanish Viceroy, who had pleaded with the local saints to protect the cities and had urged a multitude of people to repent of their sins. On the other hand, the Neapolitan culture of the first half of the 17th century, lacked the technical and scientific specialism needed to provide a rational basis of investigation to the discourse on Nature. The culture of the Counter-Reformation and Spanish hegemonic policy were both aimed at preventing the free expansion of any intellectual vitality, as was also shown by the strict controls exercised on Neapolitan academies during the 16–17th centuries. Meanwhile, the long quiescence of the volcano allowed neighbouring settlements to grow without fear of new devastation, so that just before 1631 the villages of Torre del Greco, San Giorgio, Portici, Barra, Ponticelli, San Sebastiano, Boscotrecase and San Giovanni a Teduccio, among the most affected by the eruption, totalled over 16,000 inhabitants. The tendency was to forget that the eruptions of the past had created devastation in places that now appeared idyllic. Soils rich in minerals were used to grow vines and other fruit and the long quiescence of the volcano had allowed the vegetation to become lush, with lands for grazing and areas rich in medicinal herbs. Soon these lands would be transformed into a blanket of ash and mud once again. The eruption was preceded by several precursor phenomena, which were however underestimated by many or sometimes not even recognised as such. Between the end of November and the beginning of December 1631 seismic activity had begun to make itself felt in the towns at the foot of the volcano. On 10th December, Vesuvius was shaken by strong, continuous tremors, so that the people of Torre del Greco, Massa di Somma and Pollena were unable to sleep at night. The water levels in many wells in the area dropped while in others the water appeared dirty and muddy. Meanwhile, anxiety and concern for an re-awakening of the volcano grew among the population, even if the greatest evidence of the changes were visible only by going up to the crater, as described by Braccini (1632):

> "*Moreover, as a trustworthy Ottaviano citizen relates, having climbed the mountain a month earlier up to the crater's rim, he descended to the crater's bottom; having then returned to the same place fifteen days later, he found that the ground had now risen in such a way as to make it possible to cross over from one side of the rim to the other without stepping down for any length*".

The worry increased in the following days and spread to the city of Naples, between Monday 15th and Tuesday 16th December, when Vesuvius was affected by a strong seismic crisis, accompanied by rumbles and a constant roar. Many citizens were woken during the night. At dawn on that day Vesuvius awoke with an explosive eruption accompanied by a dense column of dark ash emerging from a large fracture on the south-western flank. This is described by Giuliani (1632):

> "*It was not before long that it changed to a colossal cloud which, no longer white as before but rather dark, rising wonderfully and thoroughly piercing with great force the first layer of the atmosphere, gave shape to a variety of monstrous chimaeras and other terrifying semblance*".

While Oliva (1632) wrote:

> "*(the volcano) started belching an ash-laden smoke that took the shape of a massive pine tree…(and) having soared above the clouds continued forming mountains upon mountains, because such appeared to be the conformation of the smoke convolution*".

At about 8 am the eruption increased its in explosiveness, the ash column that had begun to emit from the crater reaching over twenty kilometres in height, quickly obscuring the sky, while large blocks of incandescent rock were launched great distances from the crater. On the afternoon of 16th December, Vesuvius was rocked by new powerful earthquakes while the sound of explosions that occurred in the crater was heard clearly throughout the area surrounding the volcano. It was in those moments that the population around Vesuvius was seized with great fear, so much so that the testimonies of the era report a multitude of people shouting that it was the Last Judgment and invoking divine mercy. The villages on the southern slopes of Vesuvius were abandoned in a hurry, and in the panic there were those who in their getaway forgot their relatives or poured out into the streets half-naked. The predominant belief of the disaster as a divine punishment was certainly the root cause of the irrationality with which the volcanic crisis was addressed. With the beginning of the eruption, the exodus of thousands of people from the stricken villages towards Naples began. Meanwhile, the Viceroy, Emanuele Fonseca Zunica, Count of Monterrey, also feared for his own safety, for the danger that the eruption might involve the city of Naples, but he decided not to move and to help the population coming from the affected areas. A public health commission was established with the help of some doctors to assess the effects of the eruption on people, particularly in the towns between the volcano and the coast. In reality, the Viceroy was more concerned about the fate of Naples, fearing that the exodus of fugitives towards the city might cause the spread of infectious diseases and it was thus not really help as such.

The incessant explosions of Vesuvius and the column of ash seemed to loom over Naples like a divine punishment. This was, at least, the sensation felt by the fugitives and many Neapolitans, exhorted to repentance by the Cardinal of Naples himself. Far from wanting to provide a rational explanation for the phenomenon, the people turned to San Gennaro (Saint Januario), the protector of Naples and to the hope that the blood contained in the famous ampoule would turn to liquid, thus presaging the salvation of the Neapolitans. The response to the violence of the eruption was a religious procession that on the afternoon of 16th December to bring the relics of San Gennaro to the church of the Madonna del Carmine, located in the eastern part of the city with the participation of important personalities and groups of the clergy and of the Viceroy himself. The procession of penitents followed the procession with great intensity and never had such a public demand for divine mercy been seen in Naples before. But the volcano did not calm down. On the evening of the 16th a rain of ash began to fall incessantly, going on all night, along with earthquakes that indicated the push of magma into the volcanic conduit. In the areas surrounding Vesuvius itself there were those who had decided to barricade themselves in their homes to protect themselves and those who had preferred to stay outdoors. Many took refuge in churches feeling more “secure” under divine protection. The ashes of the volcano, pushed by the winds at high altitude, were transported hundreds of kilometres to the south and east as far as Constantinople. On 17th December Vesuvius was shaken by increasingly violent explosions accompanied by strong earth tremors. The rains that followed the eruption carried the newly deposited ash generating powerful mudflows that affected several sectors of the volcano. When the ash also began to fall on Naples, the churches were filled with people, not so much looking for refuge, but above all for the need to confess, in the face of a phenomenon that for many Neapolitans had mystical meaning and that could not be controlled by the human will. At around 10 am on Wednesday 17th December a powerful earthquake was felt, described as unusually long and causing great fear throughout the city. At the same time the collapse of the summit of the Vesuvius crater occurred with the formation of pyroclastic flows, which flowed along the sides of the volcano towards the nearest villages. This was described by Francesco Ceraso at the time:

> "*A great smoke, composed of sulphurous ash and other bituminous matters…It suddenly blocked the paths of those who were fleeing to safety, ravaged the surrounding area with ruin and death, pulled up trees, demolished buildings, and caused a great massacre of men and animals…In the darkness caused by the cloud, most people did not know where to tread*".

The pyroclastic flows hit several towns, firstly Massa di Somma, Pollena and San Sebastiano, then Granatello (Portici), Torre del Greco and Torre Annunziata, causing serious damage and casualties. In Torre del Greco many people had just collected the basic necessities and had gone onto the streets to move towards Naples, when they were struck by the arrival of a pyroclastic flow. About 2,000 people died at the site of this event, while another 150 found salvation taking refuge inside the church of the Madonna delle Grazie.

Meanwhile, the Viceroy and the Cardinal of Naples led the refugees in a new procession, this time the Cardinal himself wanted the relics of San Gennaro and the ampoule with the blood of the saint to be carried by the procession to the Porta Capuana, then the eastern entrance to the city, which looked out at Mount Vesuvius. Amidst visions of appearances of the Saint himself and the sun suddenly coming out after the day had begun with a grey sky and light rain, there were those who shouted that it was a miracle. Showing the liquefied blood of San Gennaro to the angry volcano was the expedient to placate its anger and to instill comfort into the souls of the desperate. The processions also continued the following day, Thursday 18th December, and represented the dominant events in terms of public initiatives, which were also aimed at curbing and controlling possible misbehaviour by people as a result of fear or their state of misery.

The events following Vesuvius's most paroxysmal phase were unexpected. The rains at the time made the ashes deposited by the volcano extremely mobile, creating rivers of mud that carried heavy blocks of rock and light pumice, with extraordinary power. This is a frequent phenomenon, known as "lahar", which in many explosive volcanoes follows the phases in which large thicknesses of ash are deposited and which sometimes have devastating consequences. On 18th December the lahar struck several sectors of the volcano including Pollena Trocchia, San Sebastiano and Ottaviano, pouring out as far as the plain of Nola, north of the volcano. A description of these disastrous events was reported by Francesco Ceraso:

> "*It attacked the land near Nola with such fury that the people had no time to save themselves. Many were caught sleeping on the lower floors of their homes. The flood rose rapidly and forced people to escape to the upper floors and then to go, naked, onto their rooftops and the higher places in their homes. In fact, no-one was safe because boulders were smashing furiously against the buildings and throwing them*

> *down. This caused a great loss of life because the people could no longer escape and they fell easy prey to rapacious death. The plaintive voice of the dying carried across the waters. It was firmly believed that the flood had come once more to the Earth*"

The landscape that Vesuvius left, especially in the southern sector, was retold as a ghastly place, amidst the lifeless bodies burned by pyroclastic flows and the survivors who were still praying in the hope of salvation. Although late, the Viceroy realised that the prayers and processions were ineffective, and on 18th December he finally decided to organize a rescue mission that might effectively bring the survivors to safety and take stock of the situation with regard to the damage and the areas hit hardest by the eruption and the mud flows. The rescue operations were carried out with the help of soldiers and militias who reported terrifying evidence of the effects of the pyroclastic flows. In some areas the thickness of the ash, still hot, exceeded 2 m, and many bodies had been dragged away and incorporated into them, showing obvious burns. Rescuers recovered about 100 corpses in the Granatello (Portici) area alone, while the survivors needed immediate food, water and clothes. Operations continued in the following days, when the eruption showed signs of weakening, with phenomena whose energy was visibly decreasing. Thousands of survivors waited several days before being transported to Naples to reach those who had already moved there earlier. However, many local administrators disagreed with bringing all the refugees to Naples, not because of the fear of an epidemic, but because it was feared that food supplies for so many tired and hungry people would not be sufficient. On the contrary, the Viceroy decreed that the refugees had to find protection within the city of Naples. The rescue and reconnaissance operations in the devastated areas became more intense immediately after Christmas. The cleaning of the roads along Vesuvius and, in particular, of the royal road, which led from Naples to Salerno, was ordered. Meanwhile, the Viceroy had instructed his engineer Aniello de Falco to assess the economic damage suffered which totalled at least 16 million ducats. The death count was not accurately estimated, and moreover there was no exact count of the population before the 1631 eruption. But the human costs were, in any case, tragic, since the commentators of the era report the victims as numbering between 4000 and 10,000. Many more were left homeless and cultivated lands were devastated by pyroclastic flows and lahars. Faced with such a disaster, some intellectuals from Naples tried to provide explanations as to the causes of the eruption which went well beyond the creed established by the Counter-Reformation. The Viceroy himself erected a plaque in the city of Portici in which future generations were urged to move away from those areas already devastated by the fires of Vesuvius and that sooner or later they would be hit again by the fury of the volcano. This was an important appeal, which comments on the events of 1631 with a more rational vision, so much so that it could be considered the first manifesto of civil protection in the world. The epitaph is still there, in plain sight at the entrance of Via Gianturco in Portici, but anyone who goes to visit the place, looking around, can well understand that the exhortation of the Viceroy Emanuele Fonseca Zunica, Count of Monterrey, went absolutely unheeded.

The eruption of 1631 marked a fundamental step in the life of the Neapolitans. It was the greatest catastrophe to have befallen the area around Vesuvius in historical times and represents the event that opened a long period of activity of the open-conduit volcano, but above all it is an event that once again meant humankind had to face the problem of the significance of such catastrophes and their causes. Aristotelian culture was still dominant but a change was now close. In many of the contemporary documents such as in the writings of Gioviano di Lucca but also of Braccini himself, the calamitous event were a consequence of the horrible wickedness of human sins. This philosophy does not yet lead to a step forward in the knowledge of natural phenomena with the systematization of knowledge still being preferred to the development of new knowledge and theories. It would have to wait another forty years and the advent of the Enlightenment to find fertile ground around Vesuvius, that would go on to become the most lively of places in the debates on the nature of volcanoes and the dynamics of terrestrial processes.

3.5 The Centuries of Splendour: Travelling Around Volcanoes

How the sites around the Neapolitan volcanoes looked between the 17 and 19th centuries, and how much beauty were they able to enclose, we can only imagine from the many iconographic and written testimonies left by the ages' great painters, poets and writers (Fig. 3.30). What can be said is that the greatest interpreters of the culture and art of that time passed through Naples on their way to admire the beauties of the Neapolitan volcanoes. The refinement of their knowledge and the deepening of knowledge surrounding ancient cultures took place at these sites, with the volcanoes and the persistent activity of Vesuvius beginning with the great eruption of 1631, representing irresistible elements of attraction. It was, in fact, a moment in which, in the history of the collective mentality, the journey had acquired value for its intrinsic properties in the name of a bolder thirst for knowledge and understanding on the one hand and the pleasure of entertainment, of pure fun, on the other. What better place than Naples and its surroundings could

Fig. 3.30 View of Naples from Mergellina, in the mid-19th (anonymous author)

meet the needs of these new travellers? Travelling around Italy soon became fashionable and the name of the “Grand Tour” was assigned this fashion, a kind of cultural trip which took in Naples, Vesuvius and the Campi Flegrei as major milestones. The volcanoes, in principle, represented the spectacular power of nature to admire, through a vision that, at the beginning of the seventeenth century, was still partly linked to Aristotelian culture. Soon, however, careful observers of volcanic activity at Vesuvius strove to provide a scientific interpretation of the phenomenon as the transition to a Galilean culture occurred.

In Naples and its surroundings cultural development took place through the cross-contamination of its various populations including the Norman, Swabian, Angevin and Aragonese influences in the Middle Ages. In 1224 Frederick II of Swabia established the first secular and state university in the world, the Frederick II University of Naples. After the Medieval period, domination by Spaniards and Austrians continued from 1500 onwards until the establishment of the Bourbon Kingdom. The latter left a profound cultural mark on the Parthenopean people and during this reign the entire Neapolitan area underwent significant demographic development. In the Bourbon period, especially under the Kingdom of Charles III of the Bourbons who arrived in Naples in 1734, the rulers had flagged up their intention to give the city and its surroundings a lustre that placed it at the level of other European capitals and at the centre of the cultural life of the continent. There are so many luxurious residences of aristocrats facing the Vesuvius coast, along a road called the *Miglio d'Oro* or Golden Mile, which from the old town of Resina near Herculaneum reaches as far as Torre del Greco. Today, the *Miglio d'Oro* is identified with the complex of Vesuvius villas, all of which are listed by the *Ente Ville Vesuviane*, between San Giovanni a Teduccio and Torre del Greco (Fig. 3.31). The activism of Charles III of the Bourbons made this area a happy meeting place amidst archaeological discoveries and cultural and artistic liveliness. Here, the 18th century aristocracy could also devote itself to activities of pure leisure, such as fishing and hunting. The area along the Vesuvius coast, was ideal for building sumptuous villas, where the taste for the beautiful was highlighted by the most affirmed architects of the time, such as Vanvitelli, Vaccaro, Fuga and Gioffredo.

Between the 17 and 19th centuries Vesuvius underwent numerous eruptions, fuelling the already vibrant cultural debate in which the observation of phenomena was to become the basis of all knowledge. In addition to a place of discovery, the great variety of travellers and their heterogeneous cultural origins found in

Fig. 3.31 The Villa Vannucchi, near San Giorgio at Cremano, is one of the pearls of the *Miglio d'Oro* (the Golden Mile). The structure was commissioned by Giacono d'Aquino di Caramancio and then passed to the Vannuchi family in 1912 (from https://eventinapoli.com)

Vesuvius a place of memory, that of the object retold, of the unique landscapes that stretched from the volcano to the coasts of the Sorrento Peninsula, to the south, and area around the Campi Flegrei to the northwest. The real golden moment, which was also the culmination of each actor's expectations, coincided with that echo around the world, bouncing between the European capitals and announcing the great archaeological discoveries of Herculaneum and Pompeii in the mid-18th century with the mysterious force of volcanic nature thus revealing itself in all its drama. The skeletons of Pompeii and Herculaneum, the houses destroyed by the force of the pyroclastic flows, evoked the science of the disaster, as it became more and more clear what the volcano might cause to the nearby cities in case of a new explosive eruption. However, after the catastrophic event of 1631, the eruptive behaviour of Mount Vesuvius was mainly characterized by strombolian activity and by lava flows from the central crater or lateral vents which periodically invaded the settlements on the southern slopes (in the eruptions of 1754, 1760, 1766, 1767, 1771, 1776, 1785, 1794, 1804, 1855 and 1895–1899). This activity allowed the observation of volcanic phenomena at first hand and it was this, along with the growth of the populations around the volcanoes, though still contained, that proved the main reason leading to the foundation of the Vesuvius Observatory in 1841.

3.6 The Birth of the Vesuvius Observatory

It was 1841, when King Ferdinand II of the Bourbons started the work for what was to become the first Volcanological Observatory in the world, *il Reale Osservatorio Meteorologico e Vesuviano* - the Royal Observatory of Meteorology and Vesuvius (Fig. 3.32). The inauguration of the structure took place a few years later, in 1845, at the 7th Congress of Scientists held in the city of Naples. The establishment of the Vesuvius Observatory took place in response to the urging of many scientists and men of culture of the time, including the figure of Sir William Hamilton, made through the Naples' Academy of Sciences and supported in particular by the secretary of the Academy, Teodoro Monticelli, who formalized his request to the Bourbon Government in 1823. The Italian physicist Macedonio Melloni, assisted by Interior Minister Nicola Santangelo, were also the main actors in promoting the creation of the large scientific reference institution for world volcanology. Ferdinand II, the King of the two Sicilies, welcomed the proposal and also hoped that this new scientific institution would be the focus for research and observation on volcanoes. The first directorship was entrusted by the King to Macedonio Melloni, followed by other great scientists including Luigi Palmieri (1855–1896) and Giuseppe Mercalli (1911–1914). At that time, the city of Naples

Fig. 3.32 The historic building of the Vesuvius Observatory on the small volcanic hill of Colle Umberto (courtesy G. Ricciardi)

was already an important centre for volcanology research with the establishment of the Mineralogical Museum in 1801, and a professorship of Mineralogy at the Frederick II University in 1806. The auspices of King Ferdinand II immediately found backing, given that the birth of the Vesuvius Observatory brought about an increasing interest of scientists towards volcanic phenomena and the risks associated with eruptive activity. The easy access to the Observatory site, located on the Colle Umberto near Herculaneum and very close to the crater of Vesuvius, coupled with the almost continuous activity of the volcano itself together with its proximity to the Campi Flegrei and the city of Naples, has made this scientific structure one of the favourite destinations for Earth Science scientists from all over the world. This also resulted in a progressive change in the approach to the study of volcanology, with a more experimental orientation, based not only on simple observation, but above all on the measurement of geophysical parameters. This proved to be the basis for interpreting the nature of volcanic processes with the use of new instruments (such as seismometers), some of which are visible in the collection of objects in the historic building of the Vesuvius Observatory. The collection includes a large number of scientific instruments and include Palmieri's electromagnetic seismograph which is certainly worthy of mention. The tools and registers of seismic observations outlined the long journey completed by seismology, including that of its pioneers, Palmieri and Mercalli. The collection also

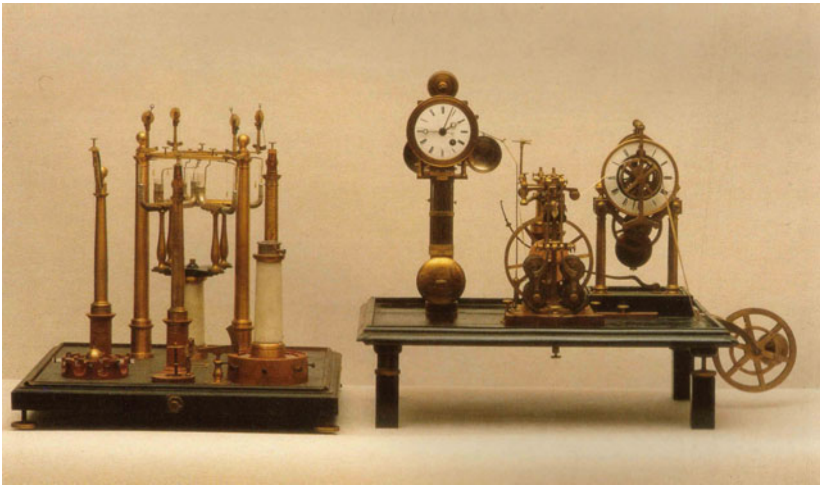


Fig. 3.33 Electromagnetic seismograph by Luigi Palmieri (1856) (OV-INGV photographic archive)

contains meteorological, magnetic, geodetic and geochemical instruments used for the study and surveillance of Vesuvius since the birth of the Observatory (Fig. 3.33).

The historic site of the Vesuvius Observatory is now an important museum, which also includes several buildings that revolve around the original nucleus of the chapel and the *Eremo del Salvatore*. The main museum building consists of a historic building that retains its original character perfectly. Since 1970, following the construction of the new work buildings a short distance downhill, the historic site has naturally evolved into the site for the preservation of precious mineralogical, instrumental and artistic collections as well as a rich historical library. The building hosting the *Museo dell'Osservatorio Vesuviuso* has been subject to a restructuring and remodelling of the teaching and exhibition routes aimed at promoting the cultural heritage it represents and contains. During its long scientific and cultural history, day-to-day life and other vicissitudes, the Observatory has acquired numerous collections of rocks, minerals, ash and volcanic materials from the historical eruptions of Vesuvius, a unique heritage of global importance for its wealth and variety (Fig. 3.34).

The site of the Vesuvius Observatory of Herculaneum was protagonist of the surveillance of Vesuvius under the direction of Giuseppe Imbò until 1944, when

Fig. 3.34 A sample of rock from Monte Somma with Phillipsite-K crystal (courtesy A. Mormone, OV-INGV photographic archive)

the volcano's most recent eruption took place towards the end of the Second World War. We are now in a period of radical change in the study of geological phenomena, with the development of modern instruments for geophysical surveillance and communication networks (the fruit of the development of military technologies) that will enable the study of volcanoes from afar with the transmission of the data acquired by geophysical instruments to large distances. And thus the interest in monitoring active volcanoes to reduce the risk of eruptions is bound to increase further. Vesuvius and the Campi Flegrei will remain the world's interpreters of this discipline, both in view of their volcanic activity and in relation to the exponential increase in the population at risk as a result of the economic boom and post-war construction. In the wake of this new approach to the study of volcanoes, and following the catastrophic earthquake that hit Irpinia in 1980, the scientific and technical staff of the Vesuvius Observatory will gradually be transferred to the University of Naples and later to a location in Posillipo. This will determine the definitive transformation of the historical site of Herculaneum, once a structure for the observation of the volcano, into a volcanological museum. With Pozzuoli's bradyseism crises in 1970–1972 and 1982–1984, the Vesuvius Observatory strengthened its seismic and geodetic monitoring network in the Campi Flegrei in order to follow the phenomena underway closely. The Vesuvius Observatory, albeit with limited means and technology, was able to handle the bradyseismic emergency which lasted from 1982 to 1984. Since then the Observatory has moved to new headquarters in the west of Naples, enormously strengthening its monitoring networks for Vesuvius, the Campi Flegrei and Ischia, which are certainly amongst the best monitored volcanoes in the world.

3.7 The Transformation of the Territory: From Thermalism to Industrial Development, the Example of the Campi Flegrei

Until the beginning of the industrial revolution, the Campi Flegrei were uncontaminated by human settlements. The volcanic hills stood in a landscape full of vegetation, surrounded by a fish-filled and crystalline sea and lakes perfect for bathing. Around the capital of the district, Pozzuoli lay the ring of the villages of Fuorigrotta, Soccavo, Pianura, Quarto, Bagnoli, Bacoli and Monte di Procida. The coastline from Bagnoli to Pozzuoli in the 1800s, saw the presence of numerous renowned and popular spa complexes. The primary sources of the local economy were the land and the sea, from which, with the favourable geographical and climatic conditions precious products were obtained. But the vital lymph of this territory, especially in Pozzuoli and Baia, was thermal and cultural tourism, the latter tied to the presence of monumental archaeological remains. Although in the 19th century archaeology and volcanism were more the preserve of an elite audience, these elements in modern times could have become a true driver of the local economy, if they had been accessible to a wider public. Unfortunately, history has not taken us in this direction. “Thermalism”, with its recreational activities and hotels, was certainly the most important element of tourism around the Campi Flegrei in the second half of the nineteenth century. From Agnano, with its magnificent spas and saunas, to Pozzuoli and Baia, there was a proliferation of thermal complexes, constructed up until 1930. With the spas, which played an important receptive function, there were adequate hotel facilities to meet the growing needs of the tourist demand. At the beginning of the 20th century local economic development included beach tourism and bathing with the structures laid out between Posillipo and Lucrino. The latter area, at the foot of Monte Nuovo, was a vacation destination for the many inhabitants of the city of Naples. Along with the Lucrino coastline, Miseno was also a much sought-after destination which nowadays is crowded with bathers during the summer season. Around 1930 in the district of the Campi Flegrei, the increase in beach tourism took place at the expense of the spas, considered more for the elite, with a consequent planning for accommodation which would meet the needs of new guests. As a result of this growing tourist development, an efficient transport network was completed and integrated in 1925 with the "Solfatara" station along the very direct Rome-Naples route, whose passage through the Campi Flegrei Fields remains a branch-line of the old Naples metro line. The Cumana railway, today still the main connecting artery between Naples and the Campi Flegrei, was inaugurated in 1889 and completed in the 1890s and until the end of the 19th and early 20th century the development of the Campi Flegrei was still aimed at the use of the area's natural resources linked to volcanism together with fishing and agriculture. But shortly thereafter, the area witnessed a slow and inexorable transformation, the metamorphosis of which took place in favour of industrial development. In 1885 the Mayor of Pozzuoli signed the ground-breaking agreement with Armstrong Mitchell and Co. of Newcastle, UK for the establishment of a naval artillery yard. In just over ten years, the British company occupied much of the coast between Pozzuoli and Arco Felice and, during the First World War employed about 8000 people. The definitive transformation of the Flegrean coast took place in 1910, when the Ilva plant was inaugurated at Bagnoli, the first complete circuit plant, manufacturing the entire range of products from cast iron to steel. Soon the vast flat area overlooking the sea between Coroglio and Bagnoli was entirely occupied by the new establishment (Fig. 3.35). The two large industrial complexes caused the break-up of the area and subsequent social upheaval, transforming peasants and fishermen into workers and creating new living conditions and requirements. However, a totally negative judgment of the type of economic development of the Campi Flegrei from the end of the 19th and the beginning of the 20th century may be excessive if one does not consider the historical-political situation of time and the dependence of the area on the metropolitan district of Naples. In fact, both Ilva di Bagnoli and Armstrong Mitchell and Co. in Pozzuoli absorbed little local labour from the Campi Flegrei and much more from Naples and neighbouring towns. All this initially created a working commuter movement and then the progressive transfer of many workers to the area of the Campi Flegrei, the industry offering secure earnings and those who devoted themselves to traditional work often chose to change their way of life, dedicating themselves to factory labour. The industrial policy, such as that of Armstrong Mitchell and Co. was very clever, offering workers' housing to the most needy and favouring the opening of a vocational training school for skilled workers. In the wake of this industrial policy, in 1967, the Pozzuoli coast also hosted Sofer, a railway and bus rolling stock industry that later acquired the Armstrong plant. During the peak development period, Sofer covered an area of about 170,000 m^2 (17 hectares or 42 acres).

Fig. 3.35 A jarring image of the early 20th century, with bathers along the coast of Bagnoli, and the ILVA plant, in the background, then running at full capacity

With industrialization, the people of the Campi Flegrei emerged from their state of backwardness, conditioned by an atavistic, fatalistic attitude, gaining a new social consciousness, which nevertheless matured with the events that subsequently took place. Indeed, the most serious transformation to record was the loss of identity of the inhabitant of the Campi Flegrei. In reality, Phlegrean society was rather complex, with the eastern villages influenced by the city of Naples, with Pozzuoli and the western towns still strong in local traditions, with the customs and mores of fishermen and farmers with large scale immigration and new styles of working leading to a gradual trend towards social uniformity. Industrialization was accompanied by demographic growth, so that between 1881 and 1981 the population of Pozzuoli grew from about 16,000–70,000. The acceleration of the phenomenon of urbanization found the political and administrative structures unprepared to solve the new problems entirely through the provision of urban planning tools that could be employed to rationally plan the use of a volcanic at risk territory. However, in spite of some attempts to adopt building regulations at the end of the 19th century, the area had to await the end of the 1960s for a town planning policy covering the Campi Flegrei. In this context, the habit of constructing houses without building standards and permits spread and the proportion of unapproved housing rose, and with it an increase in volcanic and seismic risk (Fig. 3.36a, b). The co-presence of spas and industries gave rise to a clear contrast between those in the majority who wanted to continue along the road to the industrialization of the Phlegrean coastline and those, in a minority, who considered tourism the most appropriate source of income given the geographical and geological characteristics of the area. From this clash between tourism and industry, the former emerged defeated, although later, with the failure of heavy industry and the closure of the factories belonging to Ilva and Armstrong Mitchell and Co., and, in recent times, even that of Sofer, it became clear that the industrial development policies of the area of the Campi Flegrei had produced more harm than good.

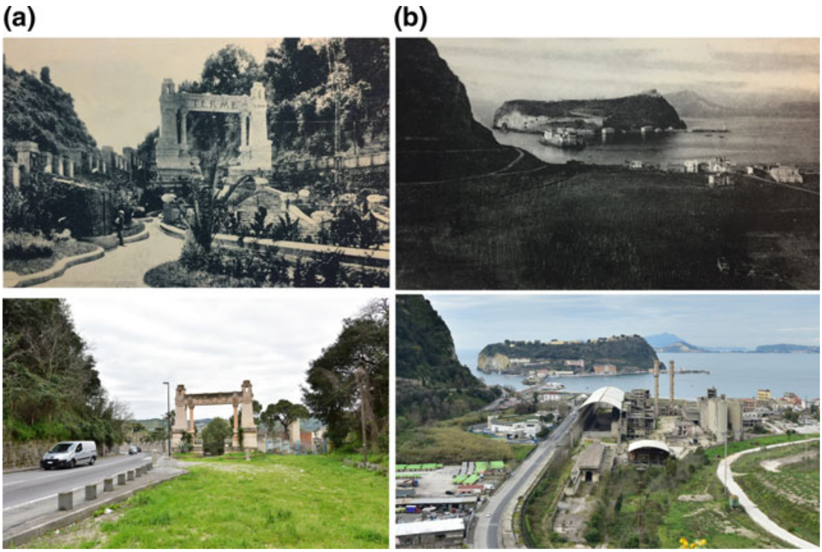


Fig. 3.36 An example of how the urbanization of the last 100 years has radically transformed the Phlegraean territory. **a** A comparison of the Agnano Terme site in a picture of the early 21th century and at the present time; **b** the same temporal comparision for the Posillipo-Bagnoli site and the island of Nisida (historical pictures from Giamminelli, 1987; present time pictures by A. Fedele)

In this process, the thermal springs and fumaroles have been gradually erased in their natural sense, and thermal bathing has been greatly reduced, with just a few sites of this type now remaining between Lucrino and Baia. An example of this transformation can be seen in the area of via Scarfoglio, about 1.5 km east of the Solfatara di Pozzuoli, a zone characterized by important fumarolic phenomena and thermal waters, which, however, has been destined for the construction of large vehicle dealerships (Fig. 3.37). The area has thus lost its original identity, strongly characterised by geothermal phenomena, and much of the commercial and industrial activities that have developed are in sharp contrast to the surrounding environment. The attempt to re-convert the former industrial sites of the Phlegrean area into areas of sustainable development and at low volcanic risk are struggling taking off, although the potential of this area in terms of tourism, culture and scientific research is still enormous. In this new development paradigm, of course, the scientific community has a key role to play.

Fig. 3.37 The uncontrolled development of Via Scarfoglio, one of the main communication routes between Naples and Pozzuoli. This area is characterized by widespread fumarolic emissions and hydrothermal phenomena, which however have not prevented its urbanization, obliterating the area's original natural character

3.8 The Economic Boom and the Increasing of Population Around Volcanoes

Immediately after the Second World War western civilization faced a lengthy period of economic crisis. To rehabilitate the economies of 17 western and southern European countries the U.S. Government sponsored the so-called Marshall Plan (the European Recovery Program, lasting from April 1948 to December 1951). Its aim was the creation of stable economic conditions in order to guarantee the survival of democratic institutions. The Marshall Plan was successful, the plan contributing to the renewal of the western European chemical, engineering, and steel industries and to a rise in gross national products of between 15 and 25%. But the question that arises from the observation of the economic development of western World is the following: what were the consequences of this development in terms of sustainability and risk? This question will be addresses in the next chapter, but here we will briefly discuss the spread of human settlements around the Neapolitan volcanoes as consequence of economic and demographic growth favoured by the quiescence of the volcanoes. These arguments are also important when addressing the discussion that follows with regard to the evacuation plans.

The demographic increase in the province of Naples and the consequent expansion of urban areas since the end of the Second World War were largely influenced by the country's economic choices following the Industrial Revolution, a process that began in the 19th century. The first mechanical plants, as noted above, began in Pozzuoli in the Campi Flegrei where, in 1885 a factory for the construction of naval artillery was opened. The increase in population and post-war industrial activity partially involved the centre of Naples itself, which by this time was already almost saturated, while migration flows took place to the neighbouring areas and around Vesuvius in conjunction with the volcano's quiescent state following its most recent eruption in 1944 (Fig. 3.38). The Campi Flegrei were also affected by this migratory flow, albeit to a lesser extent, particularly in the districts of Fuorigrotta and Bagnoli, where there was a strong phase of urban growth, especially following the expansion of the Bagnoli industrial area in 1954. As noted above, the social and environmental change within the Campi Flegrei area has been drastic and often sudden but the area around Vesuvius was even more badly affected if one thinks that until the end of the 19th century one could still feel the influence of the Grand Tour and the Vesuvius villas were still at the height of their splendour. The area around Vesuvius literally came under attack from wild "cementification" not following any town planning criteria, especially in light of the volcanic risk. In the westernmost sector of the volcano, at the border with the

Fig. 3.38 The urban expansion towards Vesuvius, which began after 1944, is very evident in these two images (top, in the early 1900s, bottom, the present day) taken from the historic headquarters of the Vesuvius Observatory (courtesy G. Ricciardi)

eastern outskirts of Naples, oil refineries and various mechanical industries were developed along the coastal strip, while between Portici and Torre Annunziata, residential areas increased enormously. Agricultural land in many areas was converted into construction sites so that the landscape of farming and forestry use was transformed into a typically urban, densely populated environment, clashing strongly with the background of Vesuvius. The northern sector of the volcano, the area of Monte Somma, suffered the same fate, although it remains more tied to a peasant tradition (Fig. 3.39). Between 1950 and the 1990s, the entire Vesuvius area witnessed uncontrolled speculative building with an exponential increase in residential areas, so as to render unrecognizable the boundaries between the towns that, especially in the coastal sector, become merely an expanse of housing and villas. In this chaotic growth, the architectural beauties left over from the time of the Grand Tour, the historic villas and palaces were engulfed and new buildings covered the lava flows arising from Vesuvius's most recent activity. With the onset of globalisation and the expansion of international markets, the industrial activities in the areas of Bagnoli and the eastern outskirts of Naples proved bankrupt. This led, as described above, to the definitive closure of Bagnoli's industrial district in 1992 and to an attempt to reclaim the area, with numerous halts and changes in

Fig. 3.39 The slope of Monte Somma. This area, when compared to the coast, has retained some of its original features, linked to rural traditions and in particular to the cultivation of vines and apricots https://wordpress.com

course, (on projects not even yet begun!), but also taking in the sector east of the city of Naples, closer to Vesuvius. Meanwhile, the quiescence of Vesuvius, which has continued unbroken since 1944, gradually transformed the volcano from a perceived condition of risk to that of a "passive" actor in the landscape. This step resulted in inevitable demographic growth that has not taken the security implications into account while the boom in the construction industry has produced the extension of the cities around the volcano with increasingly invasive settlements. Suffice to say that between 1950 and 1981, in the town of Portici alone, now one of the most densely-populated places in the world, the population rose from just over 30,000 to about 84,000. The extension of the cities around Vesuvius has taken place centripetally, approaching ever more frequently the areas that have been repeatedly affected by recent eruptions. If the quiescence of Vesuvius has caused a progressive decline in the perception of volcanic risk, the territorial management policies until the end of the last century, had continuously postponed to posterity the issue of the risks involved in spite of the continual efforts of the scientific community. Only recently have they begun to address the problem of excessive anthropic pressure in the highly volcanic areas but, as we will see in the next chapter, an organic plan for the decongestion of the most areas of greatest risk is still lacking.

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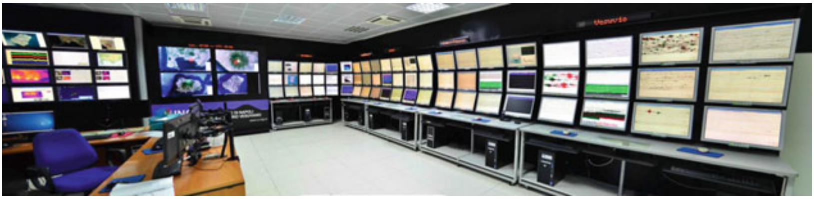
4 Volcanoes and Risk



The monitoring room of Osservatorio Vesuviano INGV (Photo A. Fedele)

What is the level of volcanic risk in the Neapolitan area? What type of eruption is the most likely to occur in the future? Where will it occur, what will its magnitude be and is it actually possible to forecast the next eruption in a timely and useful fashion? There are a number of questions which we can attempt to answer, but several important elements remain unsolved, in particular those related to eruption forecasting. Why is this? The most straightforward reason is that volcanology is not a "hard science". Given the importance to scientists attach to having their work evaluated accurately, it can be seen that the more rigorously the problem of risk assessment is organized, the more reliable the result will be. But this is not as simple as it seems, because risk assessment involves the study of complex systems such as "volcanoes" and "societies". The degree of rigour in a science seems directly related to the extent to which mathematics is used and it is this that renders a science "hard". Unfortunately, as far as the study of volcano dynamics is concerned, the mathematics and physics tools, as far as we know them, are not always appropriate for forecasting chaotic systems such as these. As we will see, the way around this problem is the same as that used in quantum mechanics, by introducing the concept of probability, since deterministic forecasts are unreliable. Eruption forecasting

S. Carlino, *Neapolitan Volcanoes*, GeoGuide,
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always has a degree of uncertainty, not only in when determining the timeframe but mainly in the assessment of the eruption's energy and duration. While we do possess means for forecasting eruptions and predicting the recommencement of activity and this allows time for evacuation (although not always if we look back to few historical cases), a major problem is the greater uncertainty in forecasting the prolongation of a volcanic crisis and the total energy release. This exposes the scientific community and the civil protection authorities to a major problem when making decisions during the crisis, in defining the extension of the exclusion zones and relocating the people at risk in areas distant from the volcano. To reduce the threat associated with the difficulty in forecasting eruptions we need to develop an efficient system of communication and cooperation between scientists, decision-makers and the public. This issue is critical in the Neapolitan area, where about 2.5 million people live in areas close to and surrounding active volcanoes.

4.1 The First Civil Protection Mission in History

Italy was one of the first countries that saw the birth of a Civil Protection Service in the 1980s following the disastrous Irpinia earthquake, with the aim of dealing with emergencies associated with natural disasters. However, we need to go much further back in time to understand how and where, in reality, what could be considered an *ante-litteram* civil protection organization came about. The source that documents this event is the well-known letter of Pliny the Younger to his friend Tacitus, in which he describes the dramatic moments during which his uncle, Pliny the Elder, lost his life trying to help the population hit by the eruption of Vesuvius in 79 A.D. The protagonist of the mission in fact, was Pliny the Elder, Admiral of the Roman fleet based in Miseno. The eruption had just begun and together with his nephew, he was observing the cloud that was rising in the distance over Vesuvius from Cape Miseno. The Admiral, a man of great culture and driven by a strong thirst for knowledge and curiosity, especially for natural phenomena, initially led him to move from Miseno towards Vesuvius, to understand this strange and unexpected phenomenon. Pliny ordered that a *liburna* (a type of small galley) put to sea, but as it was about to embark, a message arrives from Rectina, a well-known and influential woman in the circles of Imperial Rome, who was in Pompeii and desperate for assistance with all that was happening on the southern slopes of the volcano. Showing great promptness and courage in dealing with the situation the Admiral immediately ordered the large and faster quadriremes to put to sea, each of which could have taken on about 400 people. In short, Pliny the Elder transformed his journey from a scientific expedition into a rescue mission. Perhaps it was precisely the message he received from Rectina that meant he understood the true scale of the catastrophe that was taking place and it was for this reason that he chose to set sail with the largest and fastest ships to reach the disaster area as quickly as possible and help. The Admiral of the naval fleet took more than four hours to reach the coast of Herculaeneum, where, unfortunately, the situation he encountered proved more dramatic and difficult than he could have imagined. An incessant rain of ash and lapilli rendered visibility very poor and navigation difficult with even the sea conditions proving unfavourable. Pliny did not want to abandon the mission, showing great resolve, and was determined to continue. The ships lingered for a while off Herculaeneum, attempting to reach the coast. The rain of ash and lapilli gradually became more intense, but an unexpected phenomenon forced Pliny to deviate from his course. What was hindering the landing, in fact, does not seem to have been linked to poor sea conditions or to poor visibility, the ships being unable advance due to the lifting of the seabed, a swelling that was taking place due to the migration of magma towards the surface. It is perhaps possible that the large amount of pyroclastic debris falling on the seashore had contributed to making it impossible to navigate the great quadriremes. When Pliny realized the situation was critical and not wanting to risk the life of the sailors on board, he decided to turn towards Stabia, a little further south, also because the navigation in the opposite direction would have been made difficult by the wind against them. However, the most intense phases of the eruption were yet to come. Pliny the Elder, having disembarked in Stabia, had time to rest overnight, but the next day, when he was on the beach to observe the sea conditions, he was suffocated by the ash from Vesuvius that had saturated the air. His body was found three days later on the beach at Stabia, apparently unharmed. It seems, however, that the quadriremes, succeeded in bringing many of the people who had asked for help back to Miseno, at least those that had transferred to Stabia. We do not know whether, during his attempt to help, Pliny the Elder was driven more by his scientific curiosity about the phenomenon or his desire to save the population. However, the Admiral should be remembered for his great courage and for being an example of a "modern" man, for his approach to the study of natural phenomena and the way in which he was able to face the emergence of one of the best known natural disasters in history.

4.2 The Volcanic Risk in the Neapolitan Area

Living in areas exposed to natural hazards is a widespread condition for humanity, especially as a result of the demographic growth which has taken place, especially since the end of the Second World War. This has led to a rapid increase in the exposed value and the vulnerability of the areas in question. Volcanic risk is defined as the probability that an eruptive event of a given magnitude may occur (hazard) causing damage and casualties in an area with a certain exposed value and a given vulnerability. The equation *hazard x vulnerability x exposed value* quantifies this risk. While the exposed value and the vulnerability of the territory depend upon the quantity and quality of the goods exposed to risk and the potential numerical loss of life and property in the event of an eruptive event, hazard is a condition linked to the nature of the volcano itself and its evaluation is a much more complex matter. Risk can be mitigated by reducing the vulnerability of the area in question, bringing it to an acceptable level. This is a risk that can be defined as the level of human and/or material injury or loss which is considered tolerable by a society or authority in the light of a social, political, and economic cost-benefit analysis. It is essentially a judgment based on a well-reflected balancing of often conflicting values. These may be for instance economical, societal or political.

Reduction in vulnerability essentially involves urban planning interventions, and risk education policies aimed at minimizing the effects of a destructive volcanic event. However, unlike earthquakes, where earthquake-resistant buildings minimize the destructive effects of ground stress, defence against volcanoes cannot be achieved with the same strategy. Large eruptions produce substantial changes in the landscape and the volcanic products emitted, which can reach volumes of tens or hundreds of cubic kilometres, can cover areas the size of a large city with layers metres thick. The urban fabric can be buried by deposits of lahar or pyroclastic flows, against which there is no effective defence system (Fig. 4.1).

With the increase in populations exposed to volcanic risk, and to natural risks more generally, recently there has been an increase in natural disasters (Fig. 4.2a, b) and at the same time the need has arisen for scientists and civil protection authorities

Fig. 4.1 A landscape of Soufrière Hills volcano (Montserrat Island, British West Indies). The crater, on the left side, was partially demolished by the 1995 eruption. Pyroclastic flows hit the main city of the island Plymouth and buried it like a modern-day Pompeii (photo S. Carlino)

to provide exhaustive and immediate answers for the defence of vulnerable areas. This requirement involves obvious problems when dealing with natural events that are not easily predictable, and for which it is difficult to define their various evolutionary stages. A volcanic eruption, however, is not a sudden event, but is a process with a progressive evolution, typically anticipated by the appearance of precursors including earthquakes, ground deformations, changes in gas concentrations and micro-variations in the gravitational field on the basis of which it is possible to make assessments with regard to the state of criticality of the volcano (Fig. 4.3). Scientists must be able to evaluate the anomalies that are recorded in a phase of volcanic unrest, so as to understand the moment at which the critical point has been exceeded (Table 4.1). This means having to define the point at which the phenomenon in progress is now irreversible. In other words, when the energy of the processes that determine the ascent of the magma is such that it will inevitably generate an eruption. It is at this point that the evacuation of the population at risk should start, in order to guarantee their safety, avoiding a false or late alarm. Volcanic eruptions, however, are regulated by continuous feedback processes, which make the entire system non-linear (chaotic) and therefore not deterministically predictable. The assessment of volcanic danger, which should lead to a preventive evacuation before the eruption, has important social consequences and has to take into account the number of inhabitants to be moved. In case of an eruption of Vesuvius, at least 500,000 inhabitants of the Red Zone (Zona Rossa) would have to be evacuated. Although the evacuation plan provides for the large scale intervention of the civil protection authorities with assistance from the local military and police forces, a prior warning of at least three days would be required to allow the effective evacuation of such a large number of inhabitants. An initial evaluation of the three-day forecast is therefore based on a logistical requirement and not on the actual possibility of forecasting the eruption with this level of forewarning. The emergency plan for Vesuvius foresees, among other things, that a part of the population spontaneously moves away from theb Red Zone during the pre-alarm phase. Depending on the state of the volcano, the actions to be taken are defined within the emergency plan by the different levels of alert, in which the scientific and monitoring activities are decided upon depending on the assessment of the hazard. The lowest level (a “green” alert level) corresponds to the quiescence of the volcano, during which there are no significant changes in the parameters being monitored. If these changes are detected however, the protocol provides for a transition to a level of attention (“yellow”), during which there is an intensification of monitoring activities and a more frequent assessment of the condition of the volcano by the Civil Protection agency and the Italian *Commissione Grandi Rischi* (Major Risks Commission). The levels above this are those of pre-alarm (“orange”) and alarm (“red”), which, for the latter, involves the evacuation of the population from the Red Zone (Table 4.2). A critical aspect is determined by the difficulty of defining the passage between the various alert levels. The transition from the basic "green" level to "yellow", that of attention, is perhaps the least critical to evaluate, since the former is based on a sufficiently lengthy historical record and is generally characterized by a

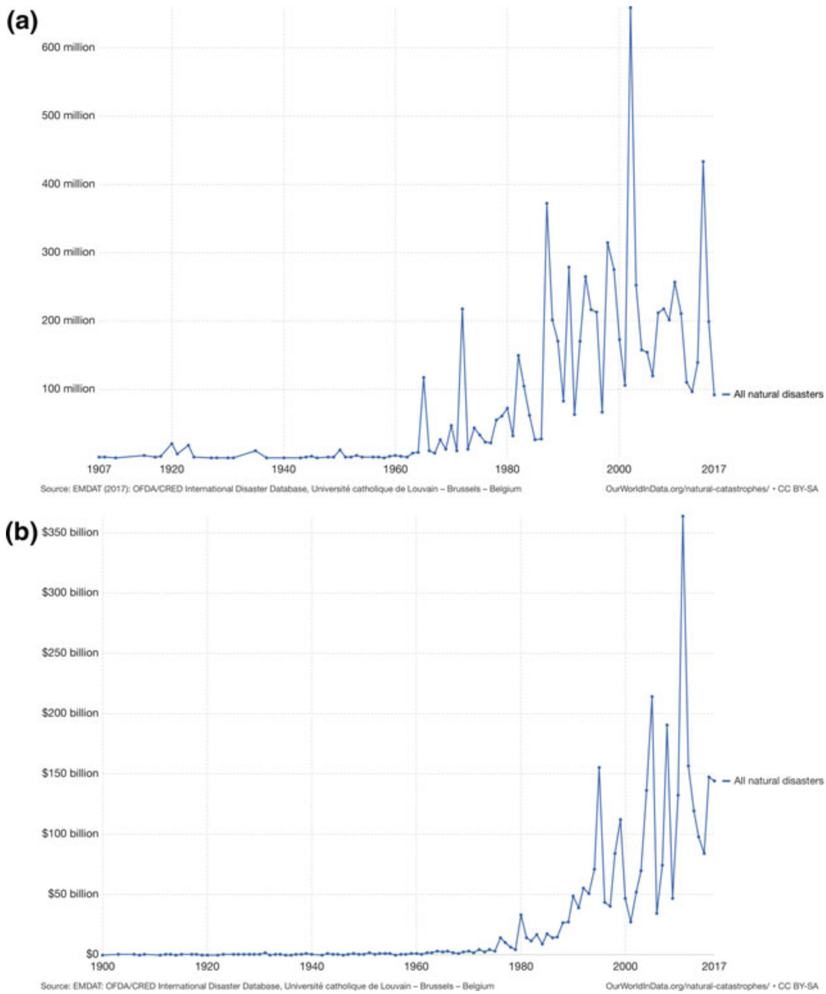


Fig. 4.2 Damage costs of natural disasters from 1907 to 2017 (**a**), and the number of people affected (**b**)

low energy of the phenomena against which anomalies emerge more easily. As we will see later, this discourse is complicated by the Campi Flegrei where, in reality, the base level is characterized by continuous instability in ground levels. The transition to subsequent levels is more complex, because there is no correlation between the energy threshold of the monitored phenomena and the alert levels (Fig. 4.4). Furthermore, when the volcano emerges from the quiescent state, the physical processes that regulate its behaviour become increasingly chaotic.

It is clear that the more accurate the forecast, the greater the possibility of the loss of human lives being reduced. However, the degree of uncertainty in forecasting decreases, but is not nullified and then only when in great proximity to the impending eruption. For this reason the short-term forecast (covering days and hours) can be considered reliable, but always and only in the field of probabilistic

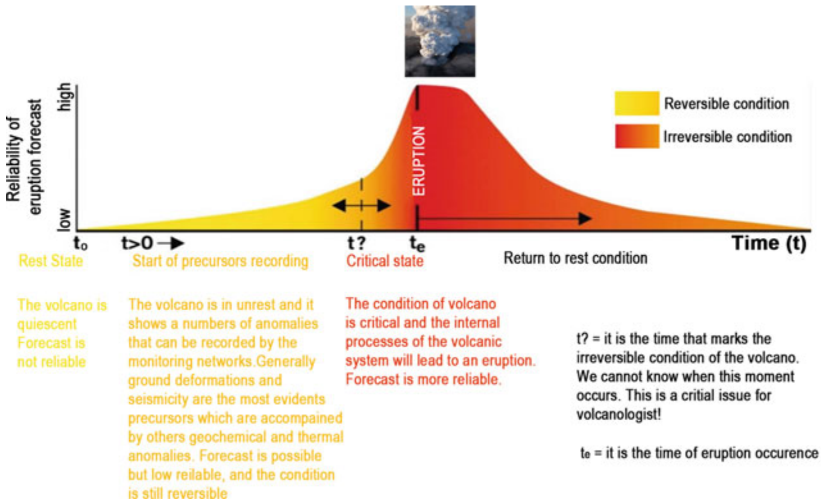


Fig. 4.3 A qualitative sketch of the reliability of volcanic eruption forecasts. For a quiescent volcano the reawakening is generally associated with the onset of seismic signals that mark the variation of stress field within the volcano, the circulation of pressurized fluids and, eventually, of magma. This dynamic is accompanied by others precursors (see Table 4.1) which make the forecast more reliable as the eruption is approached. The point at which the volcano overcomes the critical state, is the moment (t?) in which the physical processes occurring within the volcano are irreversible, that is to say the volcano will erupt. Volcanologists cannot predict the time (t?) because the processes are chaotic and the forecast is only probabilistic

Table 4.1 Precursors of the eruptions and associated causes and instruments for their recording

Precursor	Causes	How do we record it
Earthquakes	The magma rising into the crust, and the increment of pressure in the magma chamber, produce the variation of stress field in the wall rocks. A stress increment above the strength of rocks induces fracturing, with shear failure, and volcano-tectonic earthquakes occurrence. Injection of fluids or magma into the fractures and along the volcano conduit also produces long period earthquakes and volcanic tremor. The latter is typically associated to magma movement at shallow depth and is a signal of an impending eruption	Seismometers Accelerometers
Ground deformations	The pushing of magma in the shallow crust produces the deformation of the ground that can be uplifted of centimetres to meters, depending on the magma source volume, its overpressure and depth. Ground deformations can occur at different rate and generally lasts from months to years. The recording of ground deformations can give us an assessment of fresh magma volume that penetrated in the rocks	GPS networks, Levelling networks, Strainmeters, Dilatometers, Satellites
Variation of micro-gravity field	The arrival of magma or the mass (density) variation in the crust is associated to local micro-gravity change that can be measured at the surface. The gravity change, when magma arrives in the crust, must be carefully evaluated because it can be associated to others sin-processes. For instance, magma rising is correlated to ground uplift that, locally, produces a slight decreasing of micro-gravity field. Joined inversion of both gravity change and ground deformations data are very useful to constrains the depth and volume of the magmatic source	Gravimeters
Variation of thermal field	Heat contained in the magma is transferred to the rocks by conduction and can be transported by the fluids, generating advection processes (mass transport of heat). Thus, when the magma approaches the surface it produces an increase of temperature of wall rocks. The variation of the temperature is typically recorded along the fumaroles fields and the hot springs zones, where the heat transfer from magma is faster due to advection	Thermal infrared cameras Thermocouples Well log temperature Optical fiber temperature sensing

(continued)

Table 4.1 (continued)

Precursor	Causes	How do we record it
Variation of gases composition and concentration	Magma contains a number of different chemical elements a part of which, such as hydrogen and sulphur can be essolved from the melting phase and transferred to the surface as gases. Also the CO_2 (carbon dioxide) can be contained in the magma as the main gas phase. During the rising and decreasing in pressure of magma, gases phases such as SO_2, H_2S and CO_2 are released into the fracture and pores of rocks and then they reach the surface. An increase of the concentration of such magmatic gases in the fumaroles represents an important signal of possible impending eruptions	Direct sampling and laboratory analyses
Variation of magnetic and electric field	The magnetic and electric field in the Earth crust is affected by variations when magma bodies intrude at relatively shallow levels and geothermal fluids circulate into the rocks. The resistivity of rocks (i.e. the capacity to transmit the electric signal) is strongly influenced by the presence of fluids and high temperature occurrence. Also the variation of magnetic field is dependent on the temperature of magmatic body at depth	Insulated electric wires, direct-current source and devices to measure the difference of potential and input current. Magnetometers

Table 4.2 Levels of alert and technical activities reported in the Vesuvius emergency area (modified by www.protezionecivile.gov.it)

Volcano alert level	State of Volcano	National Geophysics and Volcanology Institute (INGV)	Civil Protection (DPC)	Major Risks Commission (CGR)
Base	No significant variations in the monitored parameters	Carries out ordinary monitoring and surveillance activities	Acquires, summarizes and shares information from the INGV and other Centres of Competence with the other interested parties	Receives documents relating to the surveillance and monitoring activities set up by the INGV as well as any reports produced by the other Centres of Competence with the frequency foreseen by the alert level in force
	In case of variation of the monitored parameters	*Reports any changes in values in significant parameters to the DPC with respect to the evaluation of the possible modification of the level of alert*	*Asks the CGR's assessment for variation in the alert level*	*Meets and expresses an opinion regarding an eventual change in the alert level and transmits this to the DPC*
Attention	Significant variations in the monitored parameters	Intensifies its monitoring and surveillance activities	Acquires, summarizes and shares information from the INGV and other Centres of Competence with the other interested parties, putting forward periodic requests for updates of the evaluation to the CGR	Receives documents relating to the surveillance and monitoring activities set up by the INGV as well as any reports produced by the other Centres of Competence with the frequency foreseen by the alert level in force, evaluating its updating, its remaining in force or the variation of the level of alert through specific meetings
	In case of variation of the monitored parameters	*Reports any changes in values in significant parameters to the DPC with respect to evaluation of the possible modification of the level of alert*	*Asks the CGR's assessment for variation in the alert level*	*Meets and expresses an opinion regarding an eventual change of alert level and transmits this to the DPC*

(continued)

Table 4.2 (continued)

Volcano alert level	State of Volcano	National Geophysics and Volcanology Institute (INGV)	Civil Protection (DPC)	Major Risks Commission (CGR)
Pre-alert	Further significant variations in the monitored parameters	Performs extraordinary surveillance and intensifies monitoring activities, in line with the technical function of the evaluation activated in the context of the national civil protection coordination structure and in any case in coordination with the DPC	Activates the technical function and evaluation at the national civil protection coordination facility. Through its functioning it guarantees the coordination of the evaluation activities, through which INGV and the other Competence Centres constantly keep the CGR informed	Receives documents relating to the surveillance and monitoring activities set up by the INGV as well as any reports produced by the other Centres of Competence with the frequency foreseen by the alert level in force as well as the reports of the technical function, periodically updating the remaining in force or variation of the level of alert as well as through the monitoring of the evolution of the phenomena underway towards the eruptive phase
	In case of variation of the monitored parameters	*Reports any changes in values in significant parameters to the DPC with respect to the evaluation of the possible modification of the level of alert*	*Asks the CGR's assessment for variation in the alert level while coordinating the technical and scientific activities, through the technical function and evaluation system in close cooperation with the INGV, other Centres of Competence and the CGR*	*Meets and expresses an opinion regarding an eventual change of alert level and transmits this to the DPC*

(continued)

Table 4.2 (continued)

Volcano alert level	State of Volcano	National Geophysics and Volcanology Institute (INGV)	Civil Protection (DPC)	Major Risks Commission (CGR)
Alert	Appearance of phenomena and/or trends in the monitored parameters that indicate pre-eruptive changes	Maintains the level of monitoring activity high, with further intensification of its data processing activity and the frequency of transmission of updates (press releases, bulletins, reports, etc.) to the DPC, reporting any decreases in the parameter values significant for the purposes of assessing the change in the alert level (return to the previous alert phases, down as far as the base)	Asks the CGR's assessment for variation in the alert level while coordinating the technical and scientific activities, through the technical function and evaluation system in close cooperation with the INGV, other Centres of Competence and the CGR	Follows the evolution of the phenomena in the given situation 24/7 in close connection with the DPC which ensures the provision of constant updates regarding the information of a technical-scientific character in its possession, including related documents, surveillance and monitoring activities prepared by the INGV as well as any reports produced by the other Centres of Competence, with the frequency expected from the level of alert in force. It periodically updates its evaluations for the purposes of alteration or the maintaining in force of the alert level as well as for the purpose of monitoring of the evolution of the phenomena in progress, towards the eruptive phase

(continued)

Table 4.2 (continued)

Volcano alert level	State of Volcano	National Geophysics and Volcanology Institute (INGV)	Civil Protection (DPC)	Major Risks Commission (CGR)
Ongoing eruption		Maintains the level of monitoring activity high, with further intensification of its data processing activity and the frequency of transmission of updates (press releases, bulletins, reports, etc.) to the DPC, reporting any decreases in the parameter values significant for the purposes of assessing the change in the alert level (return to the previous alert levels, down as far as the base)	Coordinates the technical-scientific activities through the technical function of evaluation, in strict contact with the INGV and other Centres of Competence and the CGR Coordinates its technical-scientific activities in close liason with the INGV and other Centres of Competence, possibly asking for an evaluation of a change in status level (a return to the previous level) to the CGR	Follows the evolution of the phenomena in the given situation 24/7 in close connection with the DPC and, through this, receives the documents relating to surveillance activities and monitoring prepared by the INGV as well as any reports produced by the other Centres of Competence with the frequency foreseen by the level of alert in force
Post-event		Carries out monitoring and surveillance activities reinforced and, in any case calibrated and commensurate with respect to the evolution of post-event phenomena. It supports the national and regional civil protection services in post-operative technical activities and reports any decreases in the values of parameters that are significant for the purpose of evaluation of the variation of the level of alert (a return to previous alert phases, down to the base level)	Coordinates its technical-scientific activities in close connection with the INGV and other Centres of Competence, possibly asking for an evaluation of a change in status level (a return to the previous level) to the CGR	Receives documents via the DPC relating to surveillance activities and monitoring prepared by the INGV as well as any reports produced by the other Centres of Competence with the frequency foreseen by the level of alert in force, periodically updating the rating. It periodically updates its assessments, for the purposes of modifying the level of alert (returning it to previous phases)

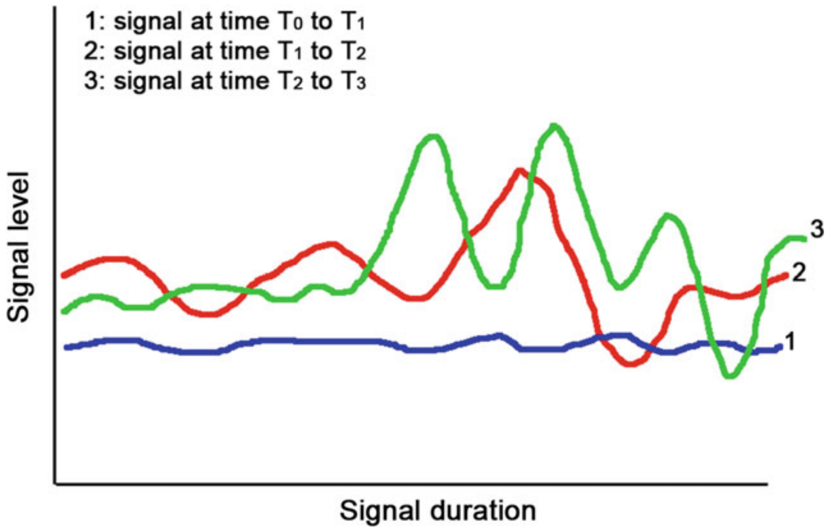


Fig. 4.4 Let us take in this picture the signals as the comparison between geophysical or geochemical records variation during different time time windows. The red and green signals are anomalous in respect to the blue one. But, how much the green signal is anomalous in respect to the red one?

evaluation. The study and research for the understanding of volcanic processes, with a rigorous scientific approach and with the use of monitoring networks, is therefore essential for the assessment of the hazard in the short term.

Things get even more complicated when we talk about long-term prediction which is purely of statistical significance and is typically performed across time-frames of tens, hundreds or thousands of years (conditional probability). For example, the probability that an eruption of Vesuvius such as that which took place in 1944 occurring in the next 200 years might be as high as 70%. It is a high value, which however does not tell us whether such an eruption will happen nor when. This value must therefore be evaluated according to its intrinsic statistical significance, which has little to do with the reality of geological processes.

The assessment of short-term hazards is an integral part of a research process that has characteristic, non-predefined times, and which in some cases are not compatible with the much faster response times required by civil protection authorities. In terms of risk mitigation, therefore, preventive intervention is necessary and does not only limit itself to operating only during the emergency phase. The necessary precondition, sufficient to reduce the risk, is the planning of cities according to the level of volcanic hazard. Furthermore, the joint intervention of scientists, civil authorities and institutions, both public and political, to guarantee the dissemination of risk culture and emergency plans, is desirable. All these conditions can ensure an immediate and adequate response by both the civil protection authorities and the population at risk in the event of an alarm.

During the process of social and demographic growth in the Neapolitan area, at least since the middle of the last century, a coherent and long-term intervention by the political authorities on the planning of metropolitan areas that extend around active volcanic areas has been absent. On the other hand, the quiescence of the volcanoes (which has lasted for over 700 years on the island of Ischia, 470 years in the Campi Flegrei and more than 70 years for Vesuvius itself) has led to inattention towards volcanic risk, the perception of which has progressively decreased. This is not only due to the lack of eruptive activity, but also due to a lack of a spread of scientific culture and historical memory. In addition, in relatively recent times, following the dissemination of news through social networks, attention towards the problem of volcanic risk in the Neapolitan area is being cyclically brought back to the fore. With at least 2,500,000 inhabitants potentially exposed to a major eruption between the Campi Flegrei and Vesuvius, it is clear that the problem of volcanic risk in the Neapolitan area cannot only involve the scientific community. The answers that the latter must provide concern the assessment of the danger represented by these volcanoes, the effects that the eruptions might produce in the most vulnerable areas and reliable predictions on the evolution of the phenomena in progress. Regardless of the efforts that scientists will be able to make in ensuring increasingly accurate predictions, the high vulnerability of the areas at risk continues. The fundamental question to be asked is therefore whether an inversion of the trend, compared to what has been observed thus far in the Neapolitan area, is sustainable, in terms of costs and policies and again, just how much and in what way the scientific community will be able to stimulate the political class in this respect? In Italy emergency policy has always prevailed over that of prevention, and this is demonstrated by the numerous natural disasters that have hit the country in the course of the last two centuries, causing thousands of victims and wreaking incalculable damage to infrastructure. The prevention instrument is therefore imperative if disasters are to be avoided and also represents a way to contain the costs borne by the State. It is well known that emergency intervention in the post-disaster phase is much more onerous than the application of risk prevention policies at the outset. Without a serious prevention policy, what are the chances that an evacuation plan will work in case of the eruption of Vesuvius, the Campi Flegrei or on the island of Ischia?

As mentioned above, a successful evacuation depends not only on the reliability of the eruption forecasts but also on other, different elements such as the cooperation between officials, scientific authorities and at-risk populations, the risk education of at-risk populations, the quality of evacuation facilities and the assistance provided by other Regions and countries. These outcomes are necessary for a successful evacuation in the case of an eruption of the Neapolitan volcanoes. In particular, the volcanic risk education and disaster preparedness of local communities could produce a better response during an emergency. The eruptions of Pinatubo in 1991 (Philippines) and the Soufrière Hills (on the island of Montserrat in the Caribbean) in 1995 are examples of how at-risk communities can prepare for disasters in a very short time (days, months). Thousands of lives were saved during the Pinatubo eruption, despite the long quiescence of the volcano and the lack of emergency preparedness of the people, because scientists were able to provide timely warnings to local communities. Similarly, about 10,000 people were gradually evacuated during the volcanic crisis at Soufrière Hills. These evacuations were successful, but it is important to note that only tens of thousands of people were involved. At Vesuvius or at Campi Flegrei, the population involved in the evacuation could be one or two orders of magnitude greater (hundreds of thousands to millions), which may necessitate the adoption of a different strategy in order to guarantee the safety of local communities in the event of an eruption.

The potentially short warning time, compounded by the large number of people needing to be evacuated, necessitates the requirement for communities to be prepared to respond quickly and appropriately to evacuation instructions. From the above considerations, schools play a vital role in volcanic risk education by providing one of the most effective and least expensive methods of maintaining appropriate risk perception.

Unfortunately, in the areas around the Neapolitan volcanic zones, a level of risk has been reached that is no longer acceptable, rendering its management increasingly difficult. It is therefore both necessary and desirable to reduce the building load, especially in the area around Vesuvius where the exposed value is higher. Is this a realistic hypothesis? And what might be the strategies to reduce the exposed value displayed in an already well-established urban context? The economic incentives provided by the Government in the past to the people of the Vesuvian Red Zone (*Zona Rossa*) to encourage relocation to safer areas have proved unsuccessful. Even the fear of the volcano is not a sufficient condition to permanently move the inhabitants to residential areas away from the most dangerous sectors. Those who live in within these zones, with a permanent job, a house and family of their own, are generally unwilling to look for a residence elsewhere just because of volcanic risk. Many of my fellow volcanologists live on the slopes of

Vesuvius! The level of perception of volcanic risk is equally low in the Campi Flegrei area, where, following the bradyseismic crisis of 1982–84, the city of Pozzuoli was evacuated due to the damage to buildings caused by continuous earthquakes and ground deformations. After about thirty years (an inexplicably long time), the city, has been completely rebuilt and has become one of the most popular residential destinations for many Neapolitans. However, the bradyseism has left tangible signs of the uplifting, clearly visible along the Pozzuoli coast and its old port is now used only as a mooring by small fishing boats. The experience of those times, with the continuous earthquakes, the fear of an eruption and the evacuation of the city, remains alive in the memory of the older inhabitants of Pozzuoli. Nevertheless, the lived experience was not handed down to the city's youngest residents and the wealth of stories and knowledge accumulated at that time, which also marked an uptick in both the development of the Neapolitan school of volcanology and an improvement in geophysical monitoring techniques, did not bring about the right levels of education in the upcoming generations and today there are still those in the Campi Flegrei who are more worried about an eruption of Vesuvius, without understanding that, in reality, they live in an active volcanic caldera!

The experiences of volcanic emergencies in other parts of the world have shown that only in a few cases have the inhabited centres at the foot of volcanoes been abandoned following catastrophic eruptions. This has taken place for small towns, but in other cases large population centres hit by eruptions have been rebuilt exactly where they were, using (and then not always) measures to improve the level of defences and reduce vulnerability. This range of choices is dictated by economic and political reasons, evaluating the number of inhabitants at risk, the productive activities in situ and the level on the social scale occupied by the affected population.

An example of the abandonment of the city following a volcanic disaster is provided by the case history of the Soufrière Hills eruption, on Montserrat Island. The volcano awoke after hundreds of years of quiescence. A series of eruptions with associated pyroclastic flows began in 1995, burying streets and buildings around the island and submerging the capital, Plymouth, like a modern-day Pompeii. Volcanic eruptions devastated about two-thirds of the island, leaving the southern sector with a barren lunar-like landscape with about 6,000 people living in the capital, where they were housed in public shelters and tents. Of the 11,000 residents, those who were able to leave the island were asked to do so voluntarily to ease the burden on shelters. The southern part of the island, where the volcano stands, is still uninhabited today.

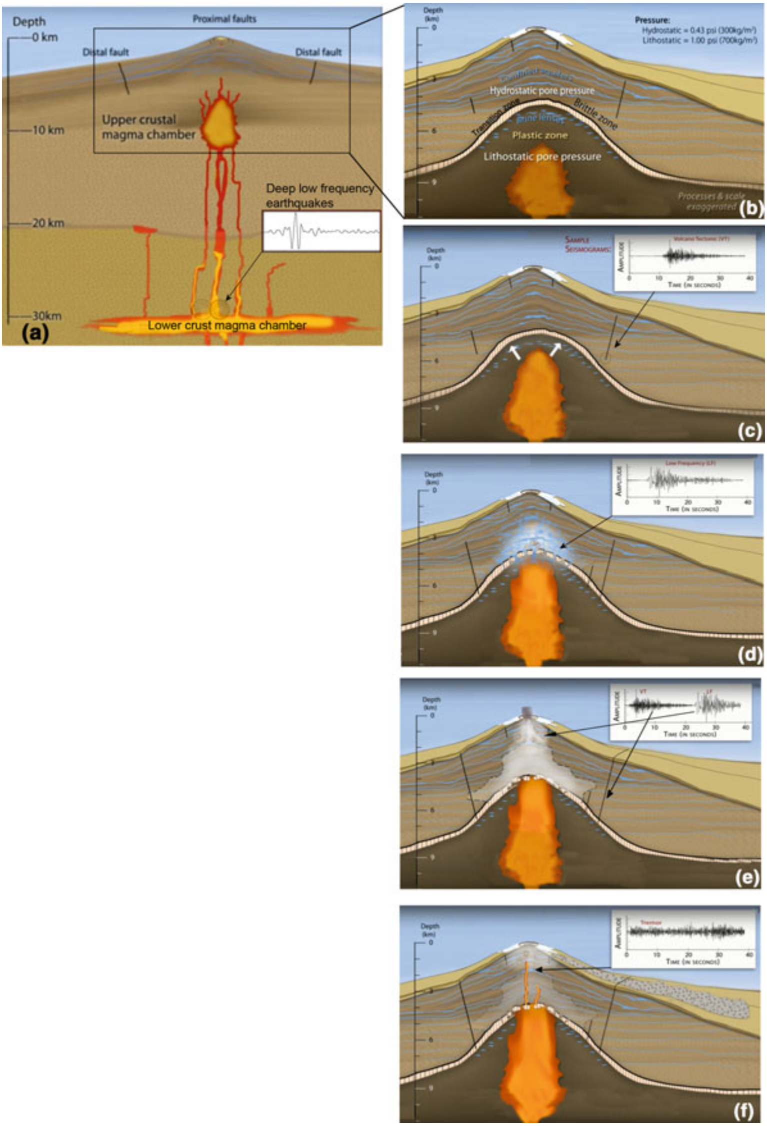
The higher the exposed value of an area affected by a natural disaster, the more difficult it can be to relocate to a safer area. The economic and social costs of relocating cities from high-risk areas, even after a catastrophic event, are very high, and re-establishing the same social organization in places other than the original ones, although safer, are practically impossible. A classic example, in this case, is Vesuvius where, from 79 A.D. until 1944, explosive and effusive eruptions, although they kept the inhabited centres at a safe distance from the crater, were not a deterrent to living in the area. Is the coexistence between humans and a volcano in densely inhabited areas like the Neapolitan one therefore sustainable? First of all we must understand that this coexistence is inevitable. It is inevitable because since the very first settlements in this area, human have drawn precious benefits from this fertile land and from the warm spring waters, have found protection for navigation in the natural coastal ravines, enjoyed the beauty of the landscapes and have been able to measure and compare themselves with the forces of Nature. However, this romantic vision of cohabitation between humans and the volcano today gives way to less reassuring scenarios for the populations at risk. Observing the current social conditions and the urban and demographic development (Fig. 4.5) of the Neapolitan volcanic area it seems impossible to think of a reversal of the tendency and towards a sustainable development of cities around the volcano. Even the catastrophic scenarios feared by the media, sometimes fomented by the scientists and researchers themselves, do not seem to help. In the face of these scenarios, from which it seems impossible to defend themselves, the Neapolitans often react in a fatalistic fashion, finding no solution to the problem. In reality, no evacuation plan can defend us from an eruption like the Campanian Ignimbrite event which took place 39,000 years ago in the Campi Flegrei, but this is so unlikely a scenario (which would require the mass evacuation of the entire Campania Region) as to not to be taken into consideration. The likelihood of such an event should only marginally affects our lives and is similar to the probability of having an air or car accident, of getting sick with serious illnesses related to smoking or food or of having a child who is not perfectly healthy. But we do refuse to get on aeroplanes, we do not avoid travelling by car or stop smoking, eating fatty food, or choose not to have children. Likewise, the probability that a catastrophic event might affect us, which is generally very low, does not affect our social choices, but rather can influence the philosophical approach of our relationship with Nature. The perception of natural disasters can only have a greater weight in our social choices through knowledge and with a change in the development paradigm for the areas at risk that no longer contemplates the indiscriminate use of the territory in any way seen fit.

Fig. 4.5 The volcanoes subject to heavy urbanization. At the centre of the image is the crater of the Astroni, in the Campi Flegrei. In the background is Capo Miseno and the Island of Ischia (photo A. Fedele)

4.3 Volcanic Earthquakes and Risk

In the first chapter we identified the most hazardous phenomena associated with volcanic eruptions. We can now examine the risk associated with volcanic earthquakes. This is an important issue because earthquakes occur during the reawakening of quiescent volcanoes and in few cases can produce heavy damages.

Long-term observations of seismicity in volcanic areas show that the approach of an eruption, particularly for dormant volcanoes, is typically associated with a significant increase in earthquakes clustered along the main volcanic-tectonic structures and around the magma chamber. The analysis of earthquake signals provides information related to the state of stress of the crust, and to the dynamics of very important processes such as fluids and/or magma migration into the rocks. For this reason earthquakes are considered the most important precursor of impending eruptions (Fig. 4.6). Furthermore, earthquakes propagate elastic waves in the crust along different paths (the greater the energy the further the distance travelled). Seismic waves, which are refracted and reflected along discontinuities at different depths and return to the surface, can be analysed as a tool for the understanding of the rheological composition of the crust beneath volcanoes.


Depth
0 km
Proximal faults
Distal fault
Distal fault
Upper crustal
magma chamber
10 km
Deep low frequency
earthquakes
20 km
30km
(a)
Lower crust magma chamber
Depth (km)
Pressure:
Hydrostatic = 0.43 psi (300kg/m³)
Lithostatic = 1.00 psi (700kg/m³)
Hydrostatic pore pressure
Brittle zone
Transition zone
Plastic zone
Lithostatic pore pressure
Processes & scale exaggerated
(b)
Sample Seismograms:
Amplitude
Time (in seconds)
(c)
(d)
VT
LF
(e)
Tremor
(f)

◀ **Fig. 4.6** Explanatory diagram of the earthquakes during the resumption of activity in quiescent volcanoes and the relative signals recorded by the seismometers with different seismic signatures recorded at the surface reflects varying geological processes. Deep low frequency earthquakes (**a**) can occur when the magma located in the lower crust rises into the conduit. This type of seismicity is only detected by sensitive seismometers. At a shallow level, in the upper crust, common seismic events include high frequency volcano-tectonic earthquakes (VT), shallow low frequency (LF) and hydride earthquakes just below the summit. In the upper part, the crust is separated into the brittle zone, with hydrostatic pore pressure, and the plastic zone, with lithostatic pore pressure (**b**). The two zones are separated by a permeable contrast (transition) zone that prevents concentrated magmatic fluids from escaping upward out of the plastic zone (**b**). The arrival of new magma pressurises the shallower reservoir and pushes the crust upward (**c**). The stress changes in the brittle volume causes volcano-tectonic earthquakes (**c**). At this point the hydrostatic pressure is transferred long distances and can trigger earthquakes at distal faults. A large enough intrusion can lead to the rupture of the transition zone (**d**) with expelling of stored magmatic fluids. Because the pressure above the transition is significantly lower than below, a sudden rupture causes depressurization of deep fluids and the resulting boiling and generation of low density magmatic vapour (**d**). This process creates low-frequency earthquakes. After the rupture, mineral precipitation reactions may quickly reseal the transition zone. During the pauses between intrusion pulses, the vapour zone can migrate higher into the uppermost part of the volcano. An addition gas pressure on the summit generates long-period (LP) events (**d**), while volcano-tectonic earthquakes can continue if the magmatic system is still pressurised. The increase in pressure close to the surface can also generate phreatic explosions (**e**). The phreatic explosions are generally accompanied by low-frequency tremor. At this point magma can migrate from the shallow source to the surface, generating hydride earthquakes which have a signature between that of VT and LP. When the magma moves into the conduit a typical tremor is recorded at the surface and may indicate an imminent eruption (**f**) (modified from *IRIS earthquake science*)

It was only during the second half of the 19th century that seismographs were first installed on volcanoes, and the link between seismic and eruptive activity began to be assessed on a firmer scientific basis. In fact, it was Luigi Palmieri, on Mt. Vesuvius, who in 1856 carried out the first systematic observations of seismic activity in volcanic areas. He was the Director of the *Osservatorio Vesuviano*, and built the first electromagnetic seismograph for the detection of ground movements. This instrument was also used in Japan until 1883, and later replaced by more modern instruments.

The record of volcanic earthquakes shows that they do not generally exceed magnitude 3 or 4, although large earthquakes ($M > 6$) can occur in some cases. The low seismic energy released in each earthquake near volcanoes is due to the lack of sufficient stress accumulation needed to provide the energies released in earthquakes of large magnitude. This may be associated with various factors such as the anomalous thermal state of the crust and the high fracturing of the medium—

resulting in a reduction in the potential seismogenetic volume—and the action of concentrated local stress due to magma or fluid pressures. Seismic signals deriving from volcanoes have a large spectrum of frequency and amplitude, the study of which allows the assessment of the sources' properties. The most frequent events are the volcano-tectonic earthquakes that typically occur during the renewal of quiescent volcanoes. These events are related to the shear fracturing of rocks subject to stress changes due to the interaction of magmatic and tectonic processes. Usually, volcano-tectonic earthquakes occur as a sequence (a "swarm") of events that are closely-clustered in time and space, without a single outstanding shock. Continuous seismic swarms were recorded during the 1982–84 unrest in the Campi Flegrei caldera, resulting in more than 25.000 earthquakes that produced weakness in buildings. Despite the relative low energy of these events, they were felt by the local population due to their low hypocentral depths (between 1 and 5 km), a characteristic that also contributed to the damage to buildings and led to the evacuation of Pozzuoli itself.

Long period and very long period earthquakes are also recorded when fluids or magma are directly involved in the fracturing process of the surroundings rocks. When the magma injection is sustained, the seismic stations around the volcano can record a continuous volcanic tremor. Earthquakes exhibiting a persistent volcanic tremor warn of an impending eruption, such that people have to be evacuated to safer areas.

4.3.1 The Case of the Island of Ischia

Significant volcano-tectonic earthquakes may occur before large eruptions or, in some cases, may trigger the eruption itself. In other cases earthquakes in volcanic areas may be associated with the interaction of tectonic and magmatic processes without producing eruptions. This is, for instance, the case of the Island of Ischia, which is sadly famous for the 28th July 1883 earthquake, which struck the northern part of the island (the Casamicciola Terme municipality) producing the almost complete devastation of the town and more that 2,300 fatalities (Fig. 4.7a–d) (see also the Ischia paragraphs in the section covering "The recent state of Neapolitan volcanoes"). In was during this event that the family (mother, father and sister) of the great philosopher, politician and writer Benedetto Croce (1866–1952) died beneath the ruins. Benedetto himself was buried beneath the ruins and barely survived. He was seventeen years old at the time and it is very likely that this tragedy conditioned the rest of his life.

Fig. 4.7 Damage from the earthquake of 28th July 1883 at Casamicciola. **a** Church of the Madonna dell'Assunta, **b** Piccola Sentinella, **c** Casa del Vescovo, **d** Hotel and Manzi Baths (INGV-OV Archive)

Fig. 4.7 (continued)

Later Benedetto Croce became one of the main actors in the debate on the respective roles of science and philosophy. He first posed a difference between the two disciplines, a distinction that concerned not so much the objects which philosophy and science deal with as the different methods which they make prevalent use of and which, in general characterize them. Behind this philosophical consideration, the 1883 event also has a very important historical relevance because it was the first great catastrophe following Italy's unification (which took place in 1861) and it was following this earthquake that the first seismic safety act was approved in Italy. The historical seismic activity of Ischia had been recognized since the 13th century and caused serious damage, thousands of casualties and, in some cases, landslides and extensive surface cracks. The earthquakes (Table 4.3) have occurred with short recurrence times together with low magnitudes, inferred from macroseismic data, and high epicentral intensity, up to I_{max} = 11 MCS, as in the case of the 1883 event. The earthquake destroyed almost 80% of the building stock. The scale of the catastrophe and the type of damage attracted many scholars of geology and seismology to the island. The studies were mainly directed towards the analysis of the behaviour of buildings subject to seismic stress and the characteristics of the ground around their foundations, in order to be able to plan the reconstruction in conditions of greater safety. There is a vast literature on this particular earthquake describing various aspects; from the mechanism of energy liberation to the latter's correlation with the dynamics of the island. The contributions of De Rossi (1883), Mercalli (1884), Palmieri and Ogliarolo (1884) and Johnston-Lavis (1885) who interpreted the genesis of the earthquake according to various theories, were fundamental. The analysis of the damage caused by the earthquake of 1883, for which there is substantial documentation, allows us to locate the event in the northern part of the island at a depth of between 1 and 2 km and with a magnitude ranging between 4.3 and 5.2. The magnitude has been derived from empirical relationships for the volcanic areas, which correlate this parameter to the intensity. The superficiality of the seismic source and the low magnitude are largely justified by the small area exhibiting high levels of damage. The damage observed, however, also has to be attributed to other elements, such as the mechanism of energy liberation, its attenuation, the structural typology of the buildings and the response of the foundations.

The scale of the damage, the renowned reputation of Casamicciola and its thermal baths and the echo that the earthquake of 1883 had at a national and global level, led the Italian government to take charge of the management for the reconstruction of this small and wonderful town. The government, with the intervention of the Minister of Public Works, Francesco Genala, in concert with the engineers of the *Genio Civile* (a State engineering body) of Naples, immediately

Table 4.3 Historical earthquakes and their intensity at Ischia Island (after De Novellis et al. 2018)

Year	Area	Intensity	Description
1275	Northern Sector	VIII–IX	Damages
1302	Eastern Area	VIII	Many buildings collapse
1557	Southeast Area	VII–VIII	Collapse of the Parish Church
1762	Casamicciola T.	VII	Damage to houses in Casamicciola Terme
1767	Eastern Area	VII–VIII	Collapse of Rotaro's Church
1769	Casamicciola T.	VIII	7 deaths, serious damage in the upper part of Casamicciola Terme
1828	Casamicciola T.	VIII–IX	28 deaths, 50 injured, serious damage and collapses in the upper part of Casamicciola Terme
1841	Casamicciola T.	VII	Cracks in the buildings
1863	Casamicciola T.	VII	Collapse of dry walls, small landslides from Mt. Epomeo
1867	Casamicciola T.	VI–VII	Buildings damaged at Casamicciola Terme
1881	Casamicciola T.	IX	129 deaths, many injured, many collapsed buildings at Casamicciola Terme and Lacco Ameno
1883	Casamicciola T.	XI	2333 deaths, 762 injured, many collapsed buildings at Casamicciola Terme, Lacco Ameno and Forio

provided strong and determined guidance during the interventions at the various sites affected by the disaster. The houses were demolished and the first shacks to re-house the residents were built in a safer area, just east of Casamicciola. In the subsequent transition from the interim to definitive works, the planned operations were based on the safety of new buildings, but also on their comfort and their economy. The main issues also involved whether people should continue living in the most seriously damaged areas or not and therefore involved the study of the problem of new buildings and the restoration of what could be recovered. The possibility of continuing to live in Casamicciola was never questioned, a sign that the government intended to undertake a hybrid reconstruction work project. However, the surveys of geologists and volcanologists clearly demonstrated the great instability of the Casamicciola soils as a result of their volcanic history and the presence of landslide-prone and heavily re-worked ground. However, this aspect made it necessary to choose certain sites for the reconstruction, and the exclusion of other unsafe ones. However, this idea (perhaps because of fears for the island's tourist economy) was largely shelved. Initially, efforts were made to favour the area of Casamicciola Marina for the new settlements, since this was the least damaged area within the municipality. In this case as well there was no re-foundation of the Marina area, and the criteria for the reconstruction work drifted ever further from the initial choices that had also been proposed by the Minister Genala. The inhabitants of the island were stubborn in the face of change and not inclined to change their habits in exchange for greater security. This story, moreover, was a repeat of the earthquakes of 1828 and 1881 that had damaged the same area. In the first case, with a provision of the Bourbon sovereign, it was decided to transfer the entire inhabited area elsewhere, even changing its name. But popular determination forced the sovereign to revoke this provision, so that the settlement of Casamicciola continued to grow on the same site and in the same fashion. In the case of the earthquake of 1881, again in an attempt to avoid bad publicity for Casamicciola, the Savoy government had blocked any discussion on the need to formulate hypotheses in favour of greater security for the town's citizens. The suggestion of the seismologist Stefano De Rossi, punctually disregarded, was emblematic. On the basis of his studies, he dramatically declared that there should be no rebuilding in that fateful place. Unfortunately, it took only two years to prove him right. The choices that followed the reconstruction of the 1883 earthquake in fact ignored the seismic issue and, moreover, the building planning was deprived of the necessary interaction with the other local components, the most obvious of which was the historical-cultural dimension. The reconstruction of the spaces freed from the rubble as well as the safest and least damaged ones relied on a regulatory plan that proposed aggregations of small neighbourhoods, a choice that saw a further deterioration of the urban fabric. In fact, what began as temporary, such as the many shacks built to the east of Casamicciola, became definitive, choosing the most economical solution but lacking historical and urban significance (Fig. 4.8).

After the 1883 event the island was subject to modest seismic activity. On 21st August 2017 an earthquake of magnitude 4.0 again struck the northern sector of the Island, causing two deaths, 42 injuries and extensive damage to Casamicciola Terme and its surroundings (Fig. 4.9a–c). As in the case of 1883, this event occurred during the summer season, when the island was full of tourists, generating high levels of concern and fear.

The events that have affected the village of Casamicciola over the last two centuries are emblematic in the history of Italian disasters, and the choices made following the earthquakes of 1828, 1881 and 1883 with regard to reconstruction, are a precise example of what should not be done in areas of seismic risk. Cities

Fig. 4.8 Shacks erected in Perrone (east of Casamicciola) dating back to the aftermath of the 1883 event and readapted for as ordinary residences, the temporary becoming definitive (photo S. Carlino)

evolve over time and should gradually adapt to the environmental conditions, in the light of the new knowledge acquired on natural hazards and by applying engineering, urban planning and social choices to improve the level of defence against natural calamities. The latest catastrophe may represent an opportunity for change or for new development. The theme is fundamental, not only for the Island of Ischia, but for the whole of Italy at high seismic risk.

I have been back to the places of the 21st August earthquake, just before finishing this book, I saw few changes and there was still rubble in the streets and people waiting for a definitive relocation. The climate did not seem to me to be one of a revival of the town, a rethink or re-establishment of the damaged area, which, given to its small size would not require the funds normally allocated following the great earthquakes. Postponing yet again the structural interventions and activating only marginal actions required to meet the expectations of a community exposed to risk in the short term, means placing a mortgage on the next disaster.

Fig. 4.9 Damage at Casamicciola from the earthquake of 21st August 2017, between Piazza Maio and Fango (photo S. Carlino)

Fig. 4.9 (continued)

See Appendix D.

4.4 Facing Volcanic Risk

4.4.1 1970–1984, Pozzuoli and the Bradyseism

To access the old port of Pozzuoli the boatmen must pass under an ancient arch, where a small isthmus enters a bend that protects the boats from the force of the sea (Fig. 4.10). The fishermen use this arch as a topographic reference to assess the rise or fall of the ground, a phenomenon associated with the volcanic dynamics of the Phlegraean area and known as "bradyseism". Today the old fishing port is used only for the docking of small boats because of the very shallow seabed that underwent an uplift of more than 3 m between 1970 and 1984. In those years Pozzuoli had to face two bradyseismic crises, which although they did not cause any victims, represented dramatic moments for the city in the Campi Flegrei. By the beginning of the 1970s the phenomenon of bradyseism had been largely forgotten, since the last time it had occurred in a very evident way had been more than 400 years previously when a lifting of about 20 m culminated in the eruption of

Fig. 4.10 The arch beneath which the fishermens of Pozzuoli have to pass with their small boats to access the old port. For fishermans the arch represents a reference level to evaluate the uplift and subsidence of the ground (photo A. Fedele)

Monte Nuovo in 1538, the most recent to have occurred in the Campi Flegrei. Knowledge regarding the phenomenon of bradyseism was scarce, and precisely in those years Plate Tectonic Theory had recently been consolidated and the study of volcanoes had begun to be carried out through the analysis of the data deriving from geophysical and geodetic monitoring. In 1970, when the city of Pozzuoli began to rise, there were no monitoring networks capable of recording land movements in real time. The topographic surveys carried out by the *Istituto Geografico Militare* in previous years, in 1953 and in 1968, had demonstrated a slow subsidence of the entire area of Pozzuoli, at a rate of about 1–1.5 cm per year (Fig. 4.11). The inversion in the movement of the ground, from the first months of 1970, was signalled by the local fishermen, who were suddenly managing to pass with their boats beneath the arch of the small harbour while standing, while it had normally been necessary to bend down. Fractures also appeared in the walls and there were steeper slopes on the gangways used for the disembarkation of passengers and cars from the ferries that connect Pozzuoli with the islands of Ischia and Procida. Until then the phenomenon was silent because it had not been

Fig. 4.11 The Serapeum of Pozzuoli in 1930. The lower level of the structure is evidenced by the constant presence of the groundwater that emerged above the floor (source www.luxinfabula.it)

accompanied by seismic activity felt by the population. The nearest seismograph was located some distance away at the headquarters of the Institute of Earth Physics at the Federico II University in Naples and this was not sufficiently sensitive to record low-energy seismic activity in the Phlegraean area. The reporting of ground level anomalies observed at Pozzuoli reached Giuseppe Imbò, just beginning the final period as head of the Vesuvian Observatory, who decided to undertake a new elevation survey performed by the engineers of the *Genio Civile* (Fig. 4.12). The results showed that the floor of the Serapeum of Pozzuoli had risen by about 70 cm since the last surveys, and that the area affected by this phenomenon included the entire city. The Vesuvian Observatory immediately obtained funding from the Ministry of Education, to increase the seismic surveillance network, acquiring Japanese-made seismographs. At the same time a new altimetric survey was carried out by the *Genio Civile*, which showed a 90 cm lift since 1968. In early March 1970 the seismograph network recorded the first slight seismic shocks, which, however, were not felt by the population due to their low energy. The statement on seismic activity alarmed the mayor of Pozzuoli who, together with Imbò, expressed the need to implement an evacuation plan for the city, which foresaw the clearing out of the ancient historic centre of Rione Terra. The lack of

Fig. 4.12 Topographical measurements at Pozzuoli carried out following the bradyseism starting in 1970 (source www.luxinfabula.it)

knowledge of the phenomenon and the inadequacy of the geophysical surveillance networks were probably the main reasons that led to the hasty choice, put in place between 3rd and 4th March, to begin the evacuation of the population of Pozzuoli (Figs. 4.13 and 4.14). However, there was a suspicion that an attempt at building speculation was at the heart of this choice. In fact, more than an evacuation, there was a forced eviction of the inhabitants of Rione Terra, who were temporarily placed in hotels and hospitals, awaiting their definitive transfer to the new residential district, the Rione Toiano district, which was to have been built a few kilometres north of Pozzuoli. Amidst the bewilderment of a population besieged by the police and the chaos caused by the closure of many of the access routes to the city, the suspicion of a building speculation manoeuvre became a conviction for many residents. The people of Pozzuoli did not agree with the choice to evict them, especially as they had not felt the few earthquakes registered by the seismographs and did not perceive any real danger. In fact, the situation until then was rather confusing. There were no data on which to define reliable scientific observations and meetings with other volcanologists were lacking. For this reason Alfred

Fig. 4.13 The evacuation of Pozzuoli during the 1970 bradyseism crisis (source www.luxinfabula.it)


Una lieve scossa di terremoto in mare ha fatto scattare il primo piano di emergenza per Pozzuoli

SEIMILA VIA DALLE CASE MA PER FINIRE DOVE?

Gli alloggi esistono: vanno requisiti

Colonne di camion militari e autobus giunti sul posto per trasferire gli abitanti del rione Terra – Alle 13 l'allarme – Momenti di panico – Con gli altoparlanti l'invito alla calma La città bloccata e il traffico deviato – Una riunione in Comune – Voci contraddittorie – «Non vogliamo fare la fine dei terremotati siciliani» gridano gli abitanti delle case che sono state abbandonate – Molti non hanno voluto andarsene – Rabbia, disperazione e paura – In nottata completato lo sgombero – La situazione sotto il controllo degli scienziati

Un piano militare non di assistenza

Fig. 4.14 "A light earthquake shock at sea triggered the first emergency plan for Pozzuoli", "SIX THOUSAND OUT OF THEIR HOMES BUT WHERE WILL THEY END UP?". The inhabitants of Pozzuoli awoke on 3rd March 1970 to this title, published in the main Naples' newspaper

Rittmann, the Director of the International Institute of Volcanology in Catania, Giorgio Marinelli, a Professor at the University of Pisa and the Japanese volcanologist Izumi Yokoyama were summoned. There were scientific meetings with very heated debates, as there was no common opinion on the way in which the phenomenon might evolve and the associated volcanic risk. However, the physical model adopted by the Japanese researchers associated the observed uplift with a high probability of an eruption. The seismic network in the Campi Flegrei was strengthened further with the intervention of the National Research Council (CNR) of Milan and its then director, Roberto Cassinis. In the meantime, the French volcanologist Haroun Tazieff arrived in Naples, installing a network of four seismographs between La Solfatara and the Rione Terra. For about two weeks the seismographs did not record any seismic activity, a fact that further fuelled the controversy between Giuseppe Imbò and the French volcanologist, the latter accusing the Italian of having invented the seismic recordings of the previous days. With the arrival of Tazieff, Paolo Gasparini was called to intervene in the debate, who was soon to take over from the Vesuvian Observatory from Imbò, and he attempted to moderate the scientific debate between the the latter and the Frenchman. Tazieff was not allowed to see the data from previous seismic records, and even the scientist himself began to suspect that the whole operation was dictated by the need to engage in a major speculative construction project. Only towards the end of March 1970 were the first earthquakes felt by the population, which continued, albeit in a very sporadic way, until 1972 in the centre of Pozzuoli when the maximum lift of 170 cm was recorded compared to 1968. The evacuees were placed in the new Toiano district, whose construction was accelerated during the final stages of bradyseismic episode which ended in 1972. For the scientists and local authorities, the 1970–72 bradyseism crisis was an unedifying experience, managed in a non-transparent fashion and rendered even more complex by the lack of knowledge surrounding the phenomenon. It was probably this last fact that determined the overcautious decision to evacuate Pozzuoli. However, during this period there was at least a new impulse to volcanological and seismological research, with funding for projects aimed at strengthening monitoring networks and assessing the seismic and volcanic hazard in the short and long term. At that time Italy had been severely tested with the devastating earthquakes of Friuli in 1976 (leaving about 1,000 people dead and more than 100,000 displaced) and the one in Campania-Basilicata in 1980 (with about 3,000 deaths and 280,000 displaced). The latter had effects across a very large area. It was as a result of these events that a National Civil Protection service was established in Italy so that when a new bradyseismic crisis occurred in Pozzuoli in 1982, the scientific community and the national and local authorities were better prepared to face the emergency. The Vesuvian Observatory, under the direction of Giuseppe Luongo, had strengthened its surveillance network, and over the course of 1982 recorded a slight tendency to ground subsidence with small-scale positive oscillations. In the summer of that year new uplifting was detected and after a few months it became obvious that a new episode of bradyseism was underway (Fig. 4.15). In January 1983, following a meeting of the Civil Defence, the then Minister Loris Fortuna went to Pozzuoli, which was a strategic area in the management of volcanic risks. As a result of his intervention the National Volcanology Group was established within the National Research Council whose task was to continue the activities carried out by the Geodynamics Project in the field of volcanology. A few months after the uplift had started again, seismic activity began, which became significant in the spring of 1983, with continuous seismic swarms, with a maximum recorded magnitude of 3.5, being clearly felt by the population, even in western Naples. Pozzuoli was shaken by hundreds of seismic events a day, which put a strain on the population frightened by the roars that accompanied the earthquakes and the continued ground movements which wrought widespread damage on the city's

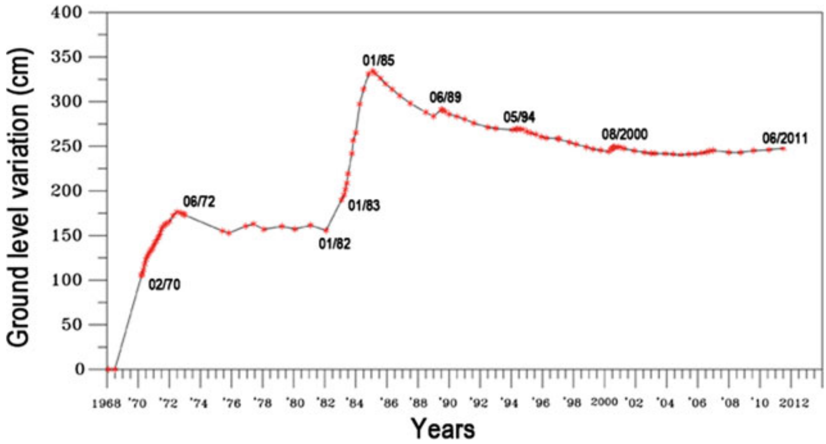


Fig. 4.15 Changes in the ground level in Pozzuoli recorded by the geodetic surveillance networks of the Vesuvius Observatory from 1969 to 2011 (www.ov.ingv.it)

ancient buildings. The seismic activity increased further between September and October 1983, reaching its peak on 4th October with a magnitude 4.0 earthquake close to the surface and causing panic among the population, damaging several buildings in the historic centre of Pozzuoli and being clearly felt in Naples. The earthquakes, mainly between 2 and 3 km down (Fig. 4.16), accompanied the continuous lifting of the ground, which reached maximum speeds of the order of centimetres per day. The Vesuvian Observatory and the National Group for Volcanology, responsible for surveillance, presented a map of seismic hazard of the Phlegraean area to the new Minister Enzo Scotti and the Prefect together with scientific documentation, showing how the level of risk in the historical centre of Pozzuoli had become excessively high, especially because of the high vulnerability of the buildings at risk. According to those responsible for monitoring, the energy of the earthquake of 4th October was very close to the maximum expected and a repetition of similar events in Pozzuoli might cause more serious damage than that recorded thus far. To this was added the concern that the phenomena under way could be precursors of an eruption, a hypothesis which, however, the Director of the Vesuvian Observatory considered less probable. Following a rolling meeting between monitoring staff, civil defence authorities and the Minister and it was decided to evacuate about 25,000 people from Pozzuoli's historic centre, the area with the highest seismic risk, while the Minister immediately hypothesized relocating people not to temporary housing but to a new, permanent housing

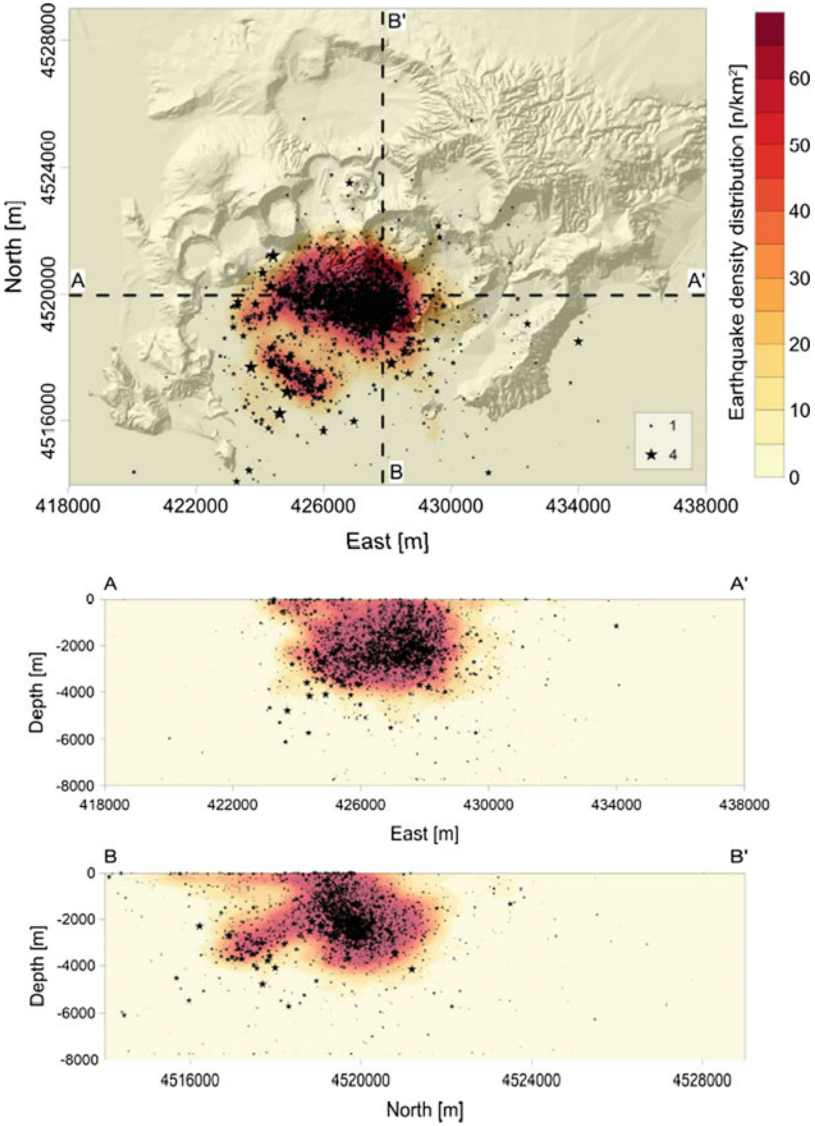


Fig. 4.16 Recent seismicity at the Campi Flegrei caldera (from 1982–2016) with magnitude ≥ 1. Above is reported the hypocenter density. Black stars represent individual events, with size proportional to event magnitudes. Below, the perpendicular sections, A–A′ and B–B′, highlighting distribution of seismicity with depth (from Castaldo et al. 2018)

settlement. The choice of the new settlement fell on the area of Monteruscello, a few kilometres north-west of the centre of Pozzuoli, considered a safer area than the coastal strip. Meanwhile, uncontrolled news circulated among the population, in a state of alarm as a result of the persistence of earthquakes and the uplifting taking place, sometimes involved catastrophic scenarios which increased the mood of panic. The evacuation of the historic centre of Pozzuoli however did allow the evolution of the phenomenon to be faced with a greater serenity. At that time, and in contrast to the previous crisis, although the respective roles of the civil protection, the Prefecture, the Region and the Municipality of Pozzuoli were not immediately clear, an effective communication system was established between the monitors, the Civil Protection Service and the citizenry and the crisis was managed with maximum transparency, especially in light of the 1970 experience, so that communication with the local community was guaranteed through the activation of a monitoring centre in Toiano which was open to the public and managed by trained personnel from the municipality of Pozzuoli.

Meanwhile, at 3 a.m. on 1st April 1984 there was a new dramatic seismic crisis with continuous swarms throughout the morning. The characteristics of these earthquakes appeared slightly different than those previously observed and it was feared that the propagation of fractures in the crust during seismic crises might allow magma to rise to the surface, beginning an eruptive phase that would have brought the entire Phlegraean area to its knees. At this stage, the Director of the Vesuvian Observatory, although advised by some colleagues to issue a pre-eruption alarm, pointed out that the phenomenon showed signs of weakening and that the energy of the system was slowly decreasing. However, the problem of evacuation that would have had to be faced in the event of an eruptive event, would have involved a much larger area than the one, already vacated, covering the historic centre of Pozzuoli. In collaboration with the new minister Giuseppe Zamberletti and following the seismic crisis of 1st April, it was decided to draw up an evacuation plan, while the Minister himself decided to activate a direct communication channel with the Vesuvian Observatory in order to have reliable news and avoid the unnecessary quarrels and alarmism that had characterized the previous period. Based on the eruptive history of the Phlegraean Fields, the scientific community drew up two different evacuation plans for both of two different eruptive scenarios: the first, of lower energy and referring to an event with characteristics similar to the last eruption of 1538 and the second, of the highest energy, referring to an eruptive event similar to the one that occurred in Agnano about 4000 years ago. On the basis of the phenomenologies registered by the surveillance network of the Vesuvian Observatory, a probability map for the opening of

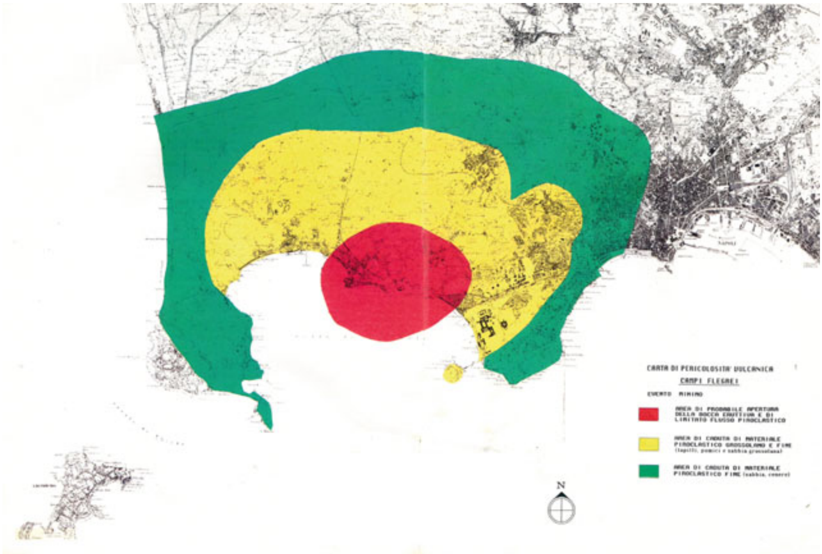


Fig. 4.17 Map of volcanic hazard for a minor eruptive event at Campi Flegrei elaborated during the 1982–84 unrest. The different colours are associated to: zone with high probability of vent opening and pyroclastic flow invasion (red); zone of large accumulation of thepra (yellow); zone of fine pyroclatic fall (green) (after Luongo 1986)

eruptive mouths located in the area around the historical centre of Pozzuoli was also developed (Fig. 4.17). It was finally established that the area to be evacuated in the event of an eruptive alarm would have had a radius of about 4 km with a centre in Pozzuoli. Meanwhile, while the plan was being prepared and the pamphlets were distributed with instructions for the citizens, the bradyseism phenomenon seemed to decrease in intensity, and in December 1984 the uplifting and seismic activity ceased, marking the end of the crisis.

Following the bradyseism of 1984, the urban fabric of the city of Pozzuoli was badly damaged, especially in the evacuated areas of the centre where the continuous seismic oscillations and deformations of the ground with a final overall uplift of about 2 m, had caused widespread damage. The 25,000 people evacuated from the historic centre were relocated to the new district of Monteruscello. This was not conceived as a new-town, nor as a temporary residence area, but as an actual neighbourhood with schools, housing, shops, infrastructure and services (Fig. 4.18). The operation Monteruscello 1 foresaw the construction of 600 houses

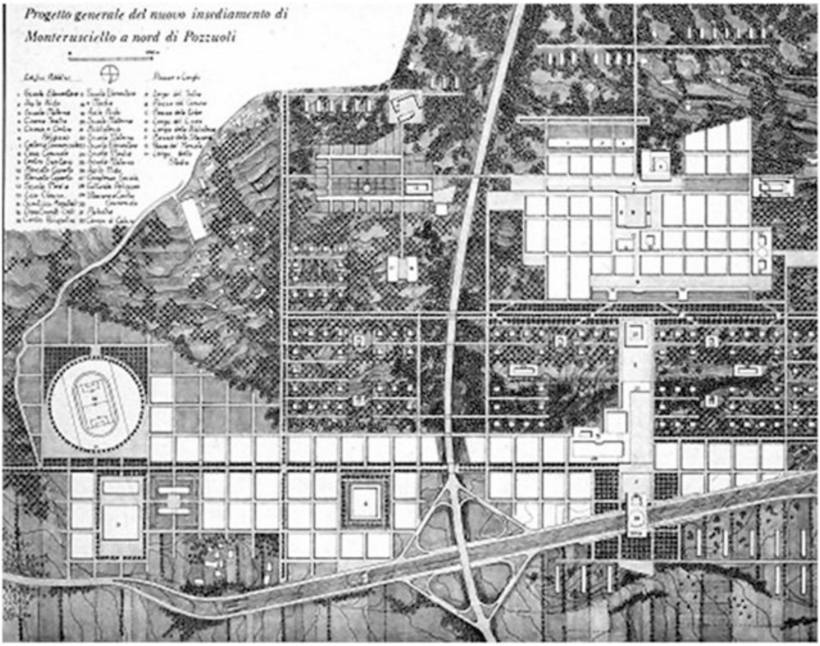


Fig. 4.18 Project of the district of Monteruscello for the resettlement of the population of Pozzuoli, displaced during the bradiseismic crisis of 1982–84 (source www.esempiarchitettura.it)

in the first instance, and a further 4000 in Monteruscello 2. On 8th September 1983, with the crisis at its peak, the first call for tenders was published for the works. In record time, in December 1984, the works of Monteruscello 1 were delivered, and in March of 1986, those of Monteruscello 2. A convincing and feasible operating method had been used to meet the needs of the population. Beyond the architectural or urban judgments on the district of Monteruscello, this was a well-planned operation, which nevertheless took on very different characteristics from that which had been planned. The measures that had to be taken for Pozzuoli, after the crisis, should have relieved the urban pressure in the areas at highest risk and should have been aimed at the elimination of dilapidated buildings, recovering and restoring what was worthy of restoration using adequate seismic criteria, with the construction of a suitable road system, and perhaps with the reconversion of the local economy towards tourism. But the post-bradyseism period was not managed with the same efficiency demonstrated during the crisis itself and saw the interest of individuals prevail over that of the community exposed to risk, bringing about a new increase in the exposed value and therefore of overall volcanic risk. Pozzuoli was in fact rebuilt without limiting the anthropic pressure that should have been contained within thresholds that would make the volcanic risk acceptable. Today the municipality of Pozzuoli has about 82,000 residents. With a priceless cultural, landscape and archaeological heritage, the city could have rebuilt and been refounded with an economy based on tourism, an activity (to the extent that this is compatible with the volcanic risk) which never took off. Since 2005, the surveillance networks of the Vesuvian Observatory have recorded a new phase of lifting, which, although contained, has again reminded the inhabitants of Pozzuoli that the Phlegraean caldera is active and that bradyseism is a volcanic manifestation with which its citizens must learn to coexist.

4.5 The Bradyseism of Pozzuoli and Its Causes: An Ongoing Problem

The ground within the Phlegraean caldera is never stationary. At least since 1970 the instrumental records of the Vesuvian Observatory, for the observation of ground movements, have underlined a periodic lifting and lowering, with its maximum manifestation located in Pozzuoli. The former was typically characterized by higher rates of increase (centimetres per month) compared to subsequent subsidence (measured in millimetres per month). The movements of the ground in this volcanic area have been going on for thousands of years, and the lifting is generally associated with the push of superficial magma, at a depth of 3–4 km in the area below the Gulf of Pozzuoli. As we will see later, there are several physical hypotheses to explain this phenomenon, which, however, cannot be demonstrated. The first physical model to explain the uplifting in the 1970s–1980s (the Mogi model) recalled the pressure increase in a spherical source (a magmatic deposit) placed in an elastic medium, at a depth that reproduces the deformations recorded on the surface by geodetic networks (Fig. 4.19). This model, however, to obtain a good fit with the experimental uplift data observed, predicted likely pressure increases that were too high and not very believable as these would have caused a catastrophic fracture of the surrounding rocks. The researchers then studied how the thermal state of the crust, which in the Campi Flegrei is characterized by high temperatures, might have influenced the level of deformation induced by a source of pressure. At high temperatures, above 350–400 °C, stressed rocks tend to deform in a ductile manner, without fracturing. In this case the behaviour of the rocks could be simulated with visco-elastic models, for which the pressure values

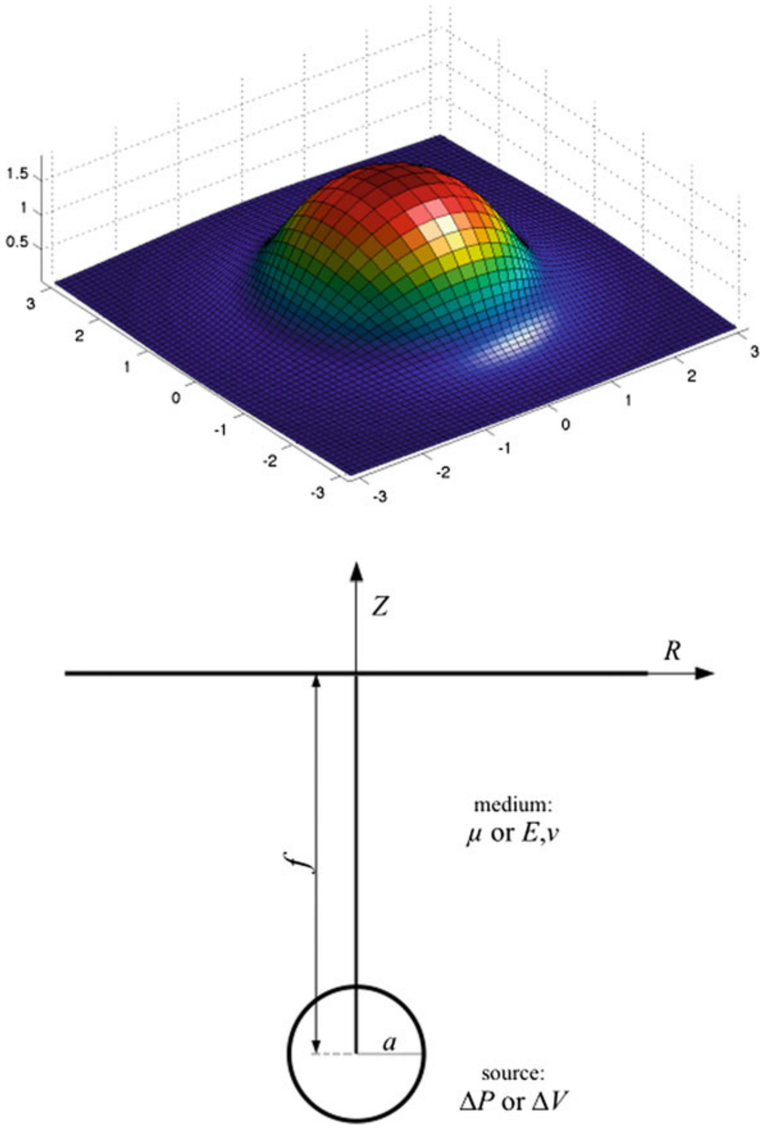


Fig. 4.19 The Mogi model, widely used in the 1970s and 1980s to justify the lifting of the ground in volcanic areas. The model provides for the presence of a spherical source of radius *a*, which subject to an increase in pressure ΔP or volume ΔV generates the displacement of the soil along the components R and Z. The medium in which the process takes place is elastic and is defined by characteristic physical parameters (μ, E, ν)

for the magmatic source required were much lower to justify the deformations observed on the surface during the bradyseism crises of the Campi Flegrei. With these models the scientists also sought to explain the lowering of the ground recorded at the end of the two great bradyseismic crises, via a process of visco-elastic relaxation of the crust. However, the geological complexity of the crust of the Campi Flegrei and the difficulty of estimating the real viscosity of the rocks affected by the deformation process placed strong limits on the development of these conceptual models. In more recent times the attention of the volcanologists has focused on the geometry of the magmatic intrusions and on the effects that the thermodynamic variations of the magmatic system of the Campi Flegrei produce on the geothermal one. The magmatic intrusions are no longer represented as spherical sources, not very likely in nature, but as tabular bodies with a horizontal (sill) or vertical (dyke) arrangement. Subsequent studies have indicated that the raising of the Campi Flegrei caldera, between 1970 and 1972 and again between 1982 and 1984, can be well reproduced by the intrusion of a magmatic sill located at a depth of 3–4 km. The studies of volcanic modelling on the resurgence of the caldera have found that the lifting can also be explained by the pressurized geothermal fluids causing porous rocks to swell. In this circumstance as well, the basic hypotheses of these studies have been applied to the case of the Campi Flegrei, showing that the process of the transfer of geothermal fluids to the surface can generate the deformations observed. This process might also explain the lowering of the ground in the phases following the unrest, with the radial migration of the fluids that have reached the surface, whose velocity is a function of the permeability of the medium being crossed. What therefore is the most realistic mechanism to explain the dynamics of the swelling Phlegraean caldera? At what depth is the magmatic source responsible for bradyseism located and is there a contribution from fluids during the lifting phases? The debate on these issues is still ongoing and does not have an answer upon which everyone is agreed. Scientists do agree that the unrest phases of 1970–72 and 1982–84 were characterized by an intrusion of a sill at shallow depth. However, the contribution to lifting could not have been only magmatic but must have had a hydrothermal component. A mixed model, in which the magma intrusion generates a disturbance in the hydrothermal circulation, and an increase in fluid pressure, could explain both the lifting and recovery of post-unrest deformation. In essence, the permanent deformation is due to the inelastic contribution of the rocks subject to stress due to pressure from magma, while the recovery of part of it could be due to degassing and the loss of fluids from the areas supplied with magma (Fig. 4.20). The difference between the proposed scenarios has implications for the perceived level of hazard from the volcanoes in the Campi Flegrei, since the volume of magma that contributes to the

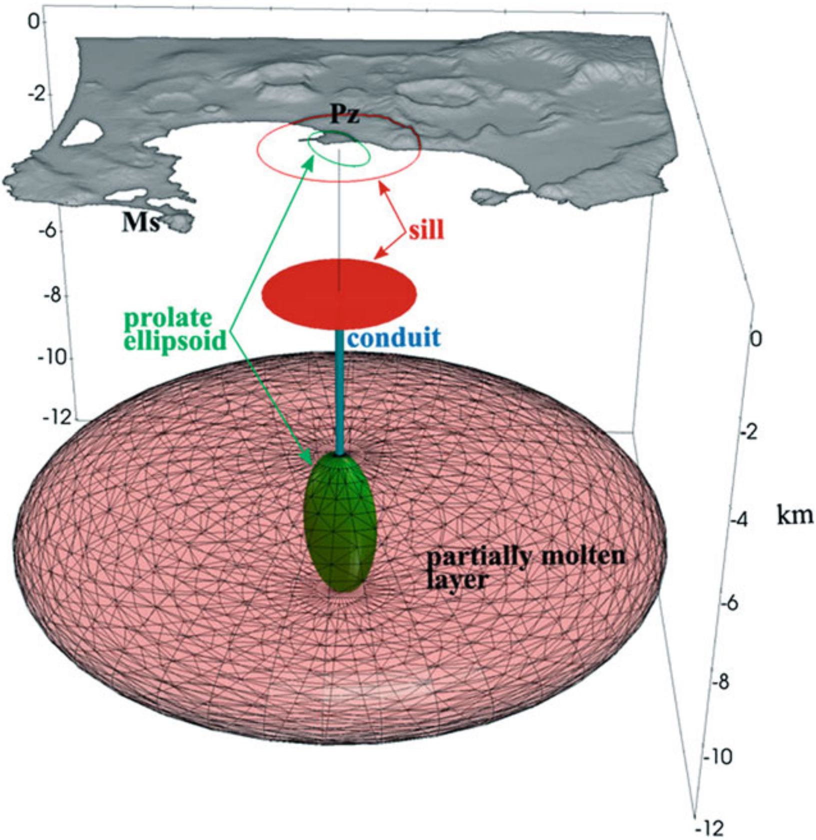


Fig. 4.20 Schematized magmatic system at the Campi Flegrei caldera, as reported in the model proposed by Amoruso et al. (2017). The different sources are reconstructed from the surface deformation data of the last 700 years. The contribution to the uplift is possibly due to a double magmatic source (a prolate ellipsoid and a sill) located at different depths

raising of the caldera provides an indication of the eruptive potential of the volcano. Considering a purely magmatic explanation for the unrest due to the intrusion of a sill that occurred during the last great crisis of 1982–84, the volume of magma involved might be of the order of 0.03–0.04 km^3. This volume, if it had erupted completely, would have generated a moderate energy event. Fortunately, there was no eruption and the magma, now cooled, might be at a temperature of around 600 °C in a thermo-rheological state, which would prevent its mobilization and therefore the eruptive process as well. However, the stress conditions in the crust evolve with each crisis of bradyseism, and subsequent episodes cannot be assessed individually with respect to the danger of an eruption. The rocks are progressively fractured each time the Campi Flegrei caldera is raised, and this process may potentially increase the probability of an eruption with the evolution of the phenomenon. A future bradyseism crisis like the one observed in 1982–84 could lead to very critical stress levels in the crust and determine its complete fracturing with a subsequent eruption. This said, the numerical models applied to the deformations observed in the Phlegraean caldera, together with the geophysical and geochemical data are not able to predict how the phenomenon will evolve in the future. The primary mechanism that gives rise to the instability of the ground observed in the Campi Flegrei remains to be clarified. The arrival of magma on the surface is, in fact, the final stage of a mechanism that originates in areas deeper down at the limit between the crust and the mantle. For this reason we need a holistic methodological approach, able to explain the phenomenon on a wider scale, and thus considering the tectonic processes, the convection phenomena in the upper mantle and the thermodynamic of the deep magmatic source. The release of the large amount of thermal energy measured in the Campi Flegrei and the continuous uplifting and subsidence of the ground might ultimately be interpreted as the effect of a convective circulation of the upper mantle, which has risen to a depth of about 20 km beneath the under the Campi Flegrei. In this case, the different eruptive phases and periods of unrest, which have occurred in the area, may be related to deterministic chaotic magma flows where different convective cells operate at decreasing temporal and spatial scales. This latter hypothesis may imply a progressive decrease in magmatic inputs and less of a hazard associated with large eruptions.

4.6 The Deep Magmatic Sources Beneath Neapolitan Volcanoes

The questions that frequently arise about volcanoes, and the risk they pose, are associated with the presence of magma sources and include “How deep are they?” and “How large is the eruptible volume of magma?” These questions are fundamental, because the assessment of the volume and depth of potential eruptible magma is a critical requisite to obtain a reliable scenario of the expected volcanic event. Very large volcanic eruptions of the Neapolitan volcanoes produced hundreds of cubic kilometres of tephra, which are spread across the volcanic district and the Campania Plain. Geological, geochemical and geophysical studies of this district, and its comparison with other volcanic areas worldwide, make it possible to conclude that the magma chambers feeding the larger eruptions, for instance below the Campi Flegrei caldera or Vesuvius, have volumes of the order of hundreds or thousands of cubic kilometres, but this assumption has not yet been verified. The study of the volumes of magma emitted during a single large volcanic event provides information about the lower limit of magma chamber volume, but does not account for the subsequent dynamic that is characterize by episodes of refilling and/or cooling. Beyond this observation, what are the scientific limits to recognising the depth and volume of magmatic sources? In responding to this question it is necessary to better understand the behaviour of the complex substance that is magma. A number of recent pieces of research on magma chambers and eruptions have been aimed at the observation of the thermal history of magma after its arrival in the crust, typically at a depth of 4–15 km. This can be done, for instance, by the analysis of the uranium-series disequilibria, crystal size and trace element zoning in crystals, such as zircon. Information on the temperature and pressure conditions of magmatic systems is recorded inside the crystals which go to make up the magma. Some components and elements contained in the magma work as a kind of "aeroplane black box", by recording the physical history of the melting phase such as the processes of cooling or melting. Volcanologists have the arduous task of deciphering the information contained in this natural black box and by analysing the crystals and the elements of erupted magma using the modern tools provided by petrology and geochemistry laboratories. The results of this research have shown that, during its thermal history, the volume of melt contained in large magma reservoirs is very low, typically below 10%, and thus their average temperature is also generally below, or close, to the solidus point (about 750 °C). The rheological behaviour of magma, its viscosity and thus its ability to move, are strictly correlated to the temperature and stress conditions under which the magma is placed. Once it rises to a certain depth, magma starts to transfer heat to the surrounding, colder rocks, via thermodynamic conductive processes and the crystallization process begins. This process is accompanied by the emission of magmatic fluids from the part undergoing solidification (degassing) with the larger the magma chamber the longer the time necessary for the cooling. In fact, as a result of the second law of thermodynamics, the magma also transfers its latent heat as it rises from crustal depth, where the surrounding medium is at lower temperatures. Overall, magma accumulation in the crust does not form as a "lake" but has a physical state that volcanologists call "mush", in which a large proportion of crystals are present (Fig. 4.21). This produces a magma of high viscosity, inhibiting its mobility. In some cases, during the cooling, if the pressure of the magma chamber is sufficiently high to overcome the strength of the surrounding

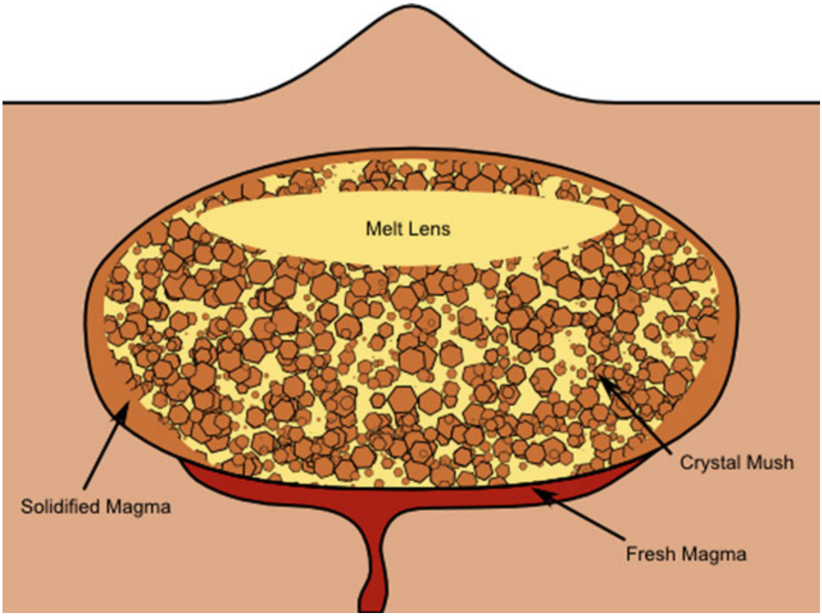


Fig. 4.21 A general sketch of a magma reservoir located at superficial crustal depths. Most of the magma is not melted, but it is composed of crystals (it is defined by volcanologist as a "mush"). Inside the reservoir melt lens can occur and the latent heat is slowly transferred outward by gas diffusion and conduction. The "mush" can be reactivated by the arrival of fresh magma from below (source www.science20.com)

rocks, isolated pockets of melted magma can migrate to the surface and produce relatively small eruptions. Basically, and generally, rapid injection of relative small amount of magma is most common and produces an overpressure above the critical strength of rocks and frequent small eruptions. When the rate of magma feeding is constant but not rapid enough, magma tends to accumulate into the crust, insted to erupt. In this case when the volume of magma is large enough its bouyacy force can induce fracturing of crust producing large but infrequent eruptions. This is one possible reason why the frequency of large eruptions is very low with respect to smaller ones.

The partial melting of magma at depth and the high percentage of crystal content make the rheology of magma similar to a fluid with very high viscosity (or to a solid with relative low viscosity). In a physical state such as this in many cases the material is rheologically comparable to that of surrounding rocks and is thus not easily recognisable using the passage of seismic waves. Seismic tomography, in fact, is the standard method used to investigate the deep crust and the Earth's interior and is very useful in detecting large discontinuities, because seismic waves undergo reflection, conversion, attenuation and velocity variation as they pass through a layered medium with a range of contrasting densities. The tomography is performed using natural earthquakes or, more frequently, artificial wave-producing sources such as explosions and seismic vibrators and then recording the P (compression), S (shearing) and other types of seismic waves at different stations located at the surface. Using an artificial source, the time taken for a seismic wave to arrive at a seismic station from the source is used to calculate the speed along the wave's ray path. By analysing the arrival times of different seismic waves, scientists are able to define slower or faster regions deep within the Earth with those arriving sooner travelling faster and later waves being slowed by something along the way. These material properties control the speed and absorption of seismic waves and careful study of the travel times and waves' amplitudes can be used to infer the main features within the Earth. One of these features is the occurrence of magma chambers below active volcanic areas. If the percentage of melt in a large chamber is sufficiently high it can be "seen" using seismic waves. Usually, for large scale and deep tomography the useful wavelength of seismic waves is greater than 1 km and therefore discontinuous structures smaller than this wavelength cannot be detected and typically, the larger the depth of investigation the smaller the resolution of the tomography. This places some limitations on the detection of partially cooled or small pockets of magma at depth. The final result of a seismic tomography, after an analysis and inversion of the data, is a 2D or 3D image of the subsurface structures that are present at different depths. This method was applied to Vesuvius in 1994 during the TOMOVES experiment. Seismic waves were produced using explosive charges and the seismic signals were recorded along different lines of seismometers. The most interesting result was the recording of large-amplitude, late arrival waves with low-frequency content. This was identified as a *P* to *S* phase conversion at a depth of about 8–10 km at the top of a low-velocity zone, which might represent a partial melting zone (Fig. 4.22).

The same method was later applied to the Campi Flegrei caldera. The deep structure of the volcano was in fact investigated during a high-resolution seismic reflection experiment. The new data suggests that a large low velocity zone, thought to be related to a magmatic sill, is present at a depth of about 7–8 km beneath the caldera (Fig. 4.23). After the publication of these studies, social media and press reports frequently interpreted the news as being about the discovery of a huge magma lake connecting the Campi Flegrei caldera and Vesuvius. As previously mentioned, this is a thermodynamic paradox, because large magma bodies at depth cannot exist in

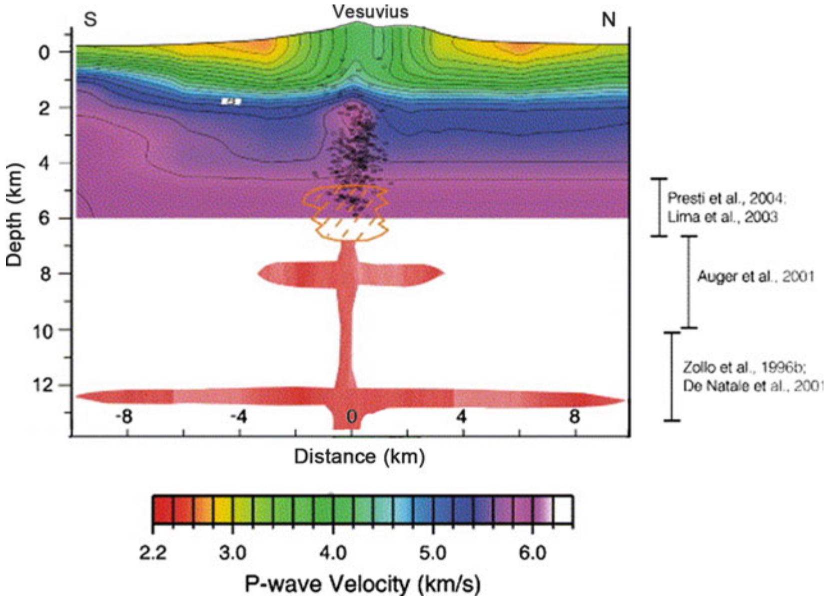


Fig. 4.22 The deep structure of Vesuvius inferred from tomography studies. A large magmatic sill is thought to be located at about 10–12 km of depth and at about 8 km by different authors (after De Natale et al. 2006)

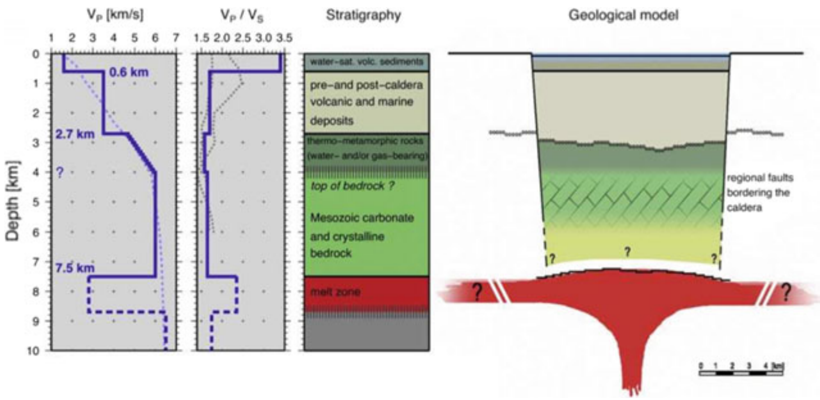


Fig. 4.23 Deep geological model of the Campi Flegrei caldera as inferred from the seismic tomography performed by Zollo et al. (2008). A decrease in P wave velocity (Vp) and an increase in the ratio between Vp and S waves velocity (Vs) occurred at 7.5 km of depth. This is indicative of a possible plastic or partially melted zone where magma accumulates in form of a sill (after Zollo et al. 2008)

form of lake, since the greater part of these bodies must be composed of crystals. Liquid magma bodies, that can be geophysically imaged, are ephemeral features and furthermore their detection might indicate an imminent eruption. The large low-velocity seismic wave layers beneath Vesuvius and Campi Flegrei may thus indicate zones where magma is stored and from which larger, past eruptions were fed. The subsequent thermal history of these reservoirs possibly led to their progressively cooling, with the formation of a crystalline-magmatic "mush". This occurs when the thermal energy transferred from a magma reservoir to the surroundings (output) is greater than the input of thermal energy provided by new magma arrival.

The thickness of the low velocity zones beneath Vesuvius and Campi Flegrei is estimated as being about 1 km, while their lateral extension has not yet been defined, due to the limitation of the area subject to seismic tomography. If the heat input due to new magma arrival is considered as negligible, this thickness of magma will take at least a million of years to lose all of its latent heat by conduction. In this case, assuming the time of magma emplacement as being equal to the age of the oldest volcanic activity, the deep magmatic reservoirs below Vesuvius and the Campi Flegrei are perhaps at a temperature of not less than 400 °C, and in any case well below its melting point (<750–800 °C). At this temperature, the viscosity is high, and even if the rocks' behaviour might be plastic, the magma cooled down to this temperature is not eruptible. Otherwise, active volcanic systems involve at least one storage of magma from which the latter, eruptible material evolves and differentiates over time. These magma reservoirs are typically open systems and the thermal history is variable due to repeated replenishment and withdrawal events. For this reason, only general assumptions can be made regarding the thermal history of magma reservoirs and heat transfer at the surface and this places major limitations when modelling heat diffusion over time, especially if robust geophysical data and data related to the geological history of the volcanoes in question are not available.

In the Neapolitan volcanic district, the depth at which large magma storages are located seems to be correlated to the sinking of the carbonate basement. Magma rises up through the upper mantle and lower crust as a result of its buoyancy force, which is a gravitational force produced by the difference in density between the magma and the rocks surrounding it. Beneath Vesuvius, for instance, as the carbonate rocks at depth have a density similar to that of trachytic magma, the sinking level of the carbonate basement may correspond to the neutral buoyancy level, where magma stops rising and begins to accumulate. The top of this basement is located at a depth of about 2 km below Vesuvius while its base is deeper, perhaps at a depth of 6–7 km. This basement deepens towards the Phlegraean district where it is not encountered in deep drillings down to depths of 3 km.

4.7 The Complexity of Forecasting the Next Eruption

4.7.1 Complexity

As already mentioned in the first chapter, the distribution of the frequency of the eruptions with respect to their energy follows a power law with the number of eruptions increasing exponentially as their energy decreases. This means that volcanic hazard associated with a large eruptive events is typically very low. More generally, this law is valid for many geological processes and morphological evolution of the Earth's surface, such as the distribution and origin of rocks, the sedimentation processes and the distribution of earthquakes across space and time. A classic example is the Gutenberg-Richter law which describes the distribution of earthquakes as a function of their magnitude. More specifically, it represents the relationship between magnitude and the total number of earthquakes in a given region and within a certain time interval. If N is the number of events exceeding a given range of magnitude M, then the Gutenberg-Richter relation establishes that:

$$LogN = a - bM$$

in which a and b are constant. The constant b is typically equal to 1 in tectonic areas, while in volcanic areas, characterized by the occurrence of many low magnitude events (seismic swarms), it may assume values equal to 2.5 (Fig. 4.24). The constant a refers instead to the number of earthquakes in the region. For any tectonic or volcanic area, it should be noted that the number of small earthquakes, recorded over a sufficiently long period of time, is much larger than the number of high magnitude events. This law can provide us with important indications with regard to the maximum earthquake expected in a given region, but cannot be used as a forecasting tool. The same applies to the distribution of the eruptions, from which information can be obtained on the statistical distribution of events, the significance of which, however, does not contain information on the physical phenomenon itself. Furthermore, for a single volcano, there is not enough information to obtain a complete database on which to perform statistical processing for the purpose of probabilistic forecasting. Moreover, the frequency of eruptions in a given volcanic area is typically lower than that of earthquakes in an active tectonic zone and this makes the statistical method (which requires a large number of samples) more easily applicable to earthquakes. An example of the distribution of the eruptions for the Campi Flegrei and Vesuvius is shown in Fig. 4.25, which illustrates the inverse proportionality between the energy and frequency of events, as observed for all the volcanoes in the world. A fundamental question is whether this data can be understood in terms of models and other approaches, such as statistical studies. For instance, deterministic models of classical physics (e.g. Newton's mechanics and continuous mechanics) cannot address many fundamental problems in geology. In this case, the relief is the introduction of probabilistic component. As previously mentioned, problems in many classes of geological processes are said to exhibit "self-organized" complexity. A system is complex when it is made up of several independent components that, by creating a sort of network, interact with each other in infinite possible ways. The end result is not the simple sum of the various elements, but is determined by their interaction. One plus one does not make two, and can even make a thousand. This is because the chaotic event always exhibits three characteristics: it is non-linear, depends upon the initial conditions and is subject to feedback mechanisms. We can formulate a simple explanatory example: atoms form chemical bonds with other atoms, thus achieving a state of minimal energy and organize molecules into new structures. The latter have emergent characteristics that do not exist in their individual constituents. A water molecule, for example, possesses characteristics that are certainly different from those of the hydrogen and oxygen atoms, which also go to make it up. Another example is when we remove the plug in a sink and observe the formation of a vortex (due to the Coriolis force) consisting of the set of water molecules that together form an emergent structure. The whirlpool that is created is a clear example of self-organization, and is, at the same time, an open system, because the molecules that constitute it change constantly, while, at the same time, it is a closed system, because the form we observe is constant and the emergent structure certainly does not depend on the individual water molecules, but on the whole. A second fundamental concept in self-organized complexity is that of deterministic chaos. This was discovered by the physicist Lorenz (1963) while studying a simple model for thermal convection in a fluid. Basically, the solutions to equations governing this process (e.g. thermal convection, turbulence, etc.,) are extremely sensitive to initial conditions. Thus, the behaviour of the equations is not predictable and only "statistical forecasts" can be done. A further example that exhibits deterministic chaos is the sliding of blocks along a surface. If a single block is pulled along a surface with a spring, the frictional interaction with the surface will result in periodic slip events. This behaviour is, in some way, predictable and resembles regularly spaced earthquakes on a fault. But the reality is ever more complex. If two slider blocks connected by a spring are pulled along the surface with two other springs, the result is chaotic. A little change in the system leads to a huge complexity. Thus, the behaviour of the system is no longer predictable, as observed in tectonics, earthquakes and volcanoes that are driven by chaotic processes.

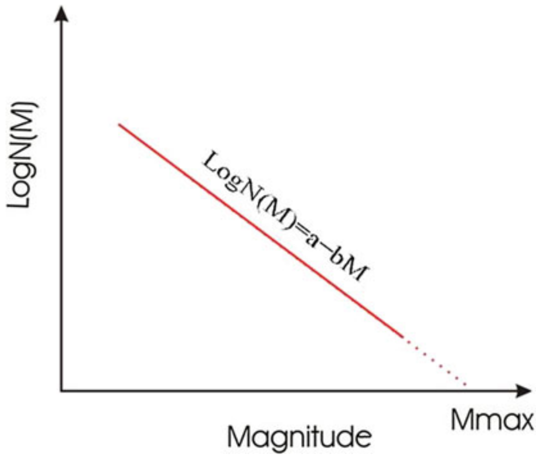


Fig. 4.24 When seismologists started measuring the magnitudes of earthquakes, they found that there were many small earthquakes when compared to large ones. This behaviour can be visualized by plotting the number of earthquakes (N) for a given magnitudes (M) against the magnitude, in a certain seismic region. From this it derives that the earthquakes' occurrence follow a characteristic distribution which is quantified using the Gutenberg-Richter law: $LogN(M) = a - bM$ (where a and b are constants). The parameter b (frequently referred to as the "b-value") is commonly close to 1.0 in seismically active regions. This means that for a given frequency of a 4.0 event there will be 10 times as many of magnitude 3.0 and 100 times as many events with a magnitude of 2.0. A variation of b-values of between 0.5 and 2 can occur, depending on the source environment of the region. During earthquake swarms b can become as high as 2, indicating a very high proportion of small earthquakes to large ones. The Gutenberg-Richter can provide information about the maximum events expected in the area, assuming that we have a complete set of records of the earthquakes occurring in a given area

When we study the volcanoes we observe many processes that volcanologists tend to analyse separately, by means of an analytical approach, a useful process that sees the breaking down of a problem into the smaller pieces necessary to solve it with each piece becoming a smaller and easier problem to solve. The study of volcanoes, in fact, involves a range of fields including fluid dynamics, thermodynamics, rheology, the stress and strain on rocks, and so forth. The process of magma rising into the crust produces various phenomena observable at the surface, such as earthquakes, ground deformations, variation in water-gas compositions, flow and temperature and micro-variations in gravity. Each observable phenomenon is a response to the dynamics of the magma during its migration from the upper mantle to the shallow crust and to local and regional tectonics. The total of

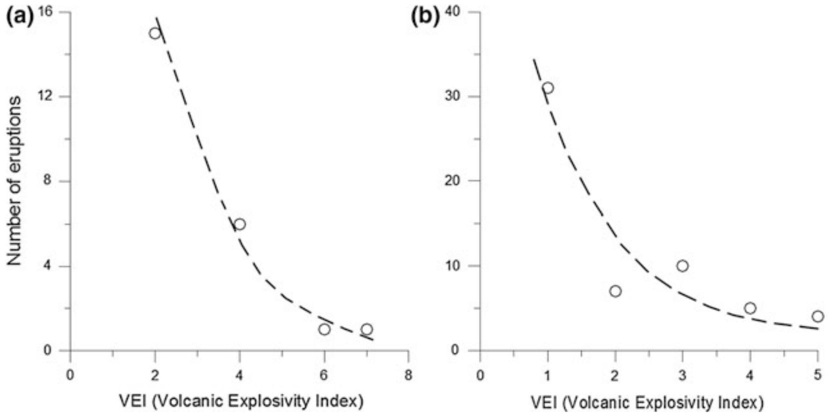


Fig. 4.25 **a**, **b**. Distribution of the number of eruptions versus their energy (VEI) for the Campi Flegrei (**a**) and Vesuvius (**b**). The distribution follows a power law similar to that of the Gutenberg-Richter law applied for the statistical analysis of earthquakes

these phenomena are then subject to feedback mechanisms, so that the system and its properties should be viewed as a whole (the holistic approach), and not just as an assemblage of parts (the analytical approach). This represents a further limit in solving equations that are unable to reproduce chaotic and self-organized critical systems. Recently, computer simulations have been widely used to solve very complex problems while simulating volcano dynamics using large amounts of data provided by the development of high-tech geophysical monitoring networks and seismic tomography experiments at volcanoes. These data sets can improve the robustness of the computer modelling but, are not sufficient to provide reliable forecasts, because of the reasons outlined above. When talking about geological processes, Stephen Wolfram (2002) noted the necessity to investigate this “new kind of science”, that is the study of complexity.

4.7.2 How: The Most Probably Eruptive Scenario

During the last unrest at Campi Flegrei the concern about possible eruptions in Neapolitan area was increased and the echo of the crisis and the evacuation of Pozzuoli reached the central government. In 1991 the Civil Protection Department and the National Volcanology Group (GNV) with the guide of Franco Barberi appointed a commission to establish the guidelines for evaluating the volcanic risk in Campania. The attention was posed firstly on Vesuvius whose planning strategies was delineated in 1995. During that period there was an implamantation of the monitoring networks of Neapolitan volcanoes and a development of many volcanological studies aimed to collect new geological data and to study the effect of pyroclastic flow and ahs fall on the high urbanized territory. Otherwise, the information above illustrates that the study of the geological history of volcanoes, as well as the knowledge we have today with regard to their deep structure, are not sufficient elements to provide a deterministic forecast. For this reason the volcanologists use the term “scenario”, rather than “forecast”, to identify the most probable expected event and study its potential effects on the affected area. Based on the severity of a given scenario—and therefore on the consequences that it may have in terms of the extent of the areas potentially exposed to the invasion of pyroclastic flows, lahars or affected by falling ash—the emergency plan is drawn up. As far as Vesuvius is concerned, the commission charged with updating the emergency plan has stated that the reference scenario is a sub-Plinian type event

Fig. 4.26 The Red Zone (“*Zona Rossa*”) for Vesuvius as laid out in the Vesuvius’ Emergency Plan (source www.protezionecivile.gov.it). This represents the most impacted zone that must be evacuated in the event of a reawakening of the volcano. The reference scenario for this plan is an eruption similar to that of 1631

(VEI = 4), similar to that which took place in 1631. This scenario involves the formation of an eruptive column several kilometres high, the fall of volcanic bombs and blocks in the immediate vicinity of the crater and smaller particles—ash and lapilli—as far as several tens of kilometres away, and the formation of pyroclastic flows that could spill over the slopes of the volcano for a few kilometres. A scenario of this kind, which would mainly affect the cities located south of the volcano, foresees for the evacuation of about 500,000 people from the entire Red Zone. The latter is the area in which there is the greatest risk of invasion by pyroclastic flows and lahar, and covers about 350 km^2 across twenty-five municipalities (Fig. 4.26). On the basis of the above scenario, a second area was also defined, the Yellow Zone (*Zona Gialla*), exposed to the fallout of volcanic ash

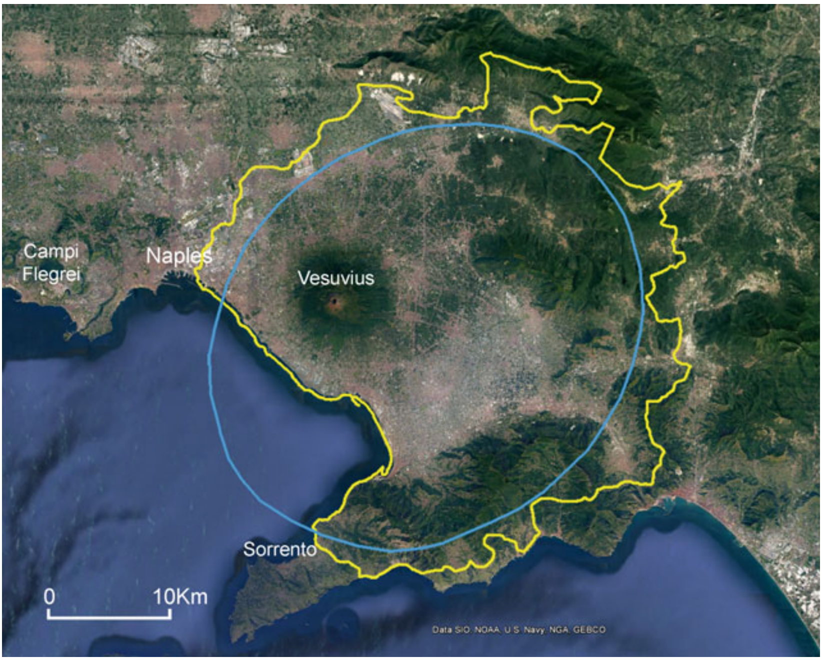


Fig. 4.27 The Yellow Zone ("*Zona Gialla*") for Vesuvius. This indicates the area where substantial ash accumulations may occur resulting from the explosive activity of the volcano. The blue line indicates the approximate area within which accumulations of ash higher than 300 kg/m^2 may occur (probability of 5%). This quantity is defined as dangerous due to the risk of roof collapse (source: www.protezionecivile.gov.it)

(Fig. 4.27). It covers sixty-three municipalities in the provinces of Naples and Salerno and three districts of the Municipality of Naples. The value taken as a reference of the level of risk (the one that could cause the collapse of the roofs of buildings), is 300 kg/m^2, equivalent to about thirty centimetres of accumulation on the ground.

Recently, in August 2016, the emergency planning for the volcanic risk of the Campi Flegrei was updated, during which the area of the new Red Zone to be evacuated as a precautionary measure in case of eruption, was defined, together with the Yellow Zone, that is potentially exposed to a high concentration of falling ash (Figs. 4.28 and 4.29). As for Vesuvius, the Red Zone and Yellow Zone have been defined by the Department of Civil Protection, in agreement with the Campania Region, and based on the indications provided by the scientific community. According to the latter, a statistical analysis has been carried out showing that, in the event of a re-awakening of volcanic activity in the Campi Flegrei, there is about a 95% probability that the eruption will be on a scale less than or equal to that of a medium energy eruption. According to the Civil Protection Department, a medium energy eruption, as a reference scenario, corresponds to a reasonable choice of

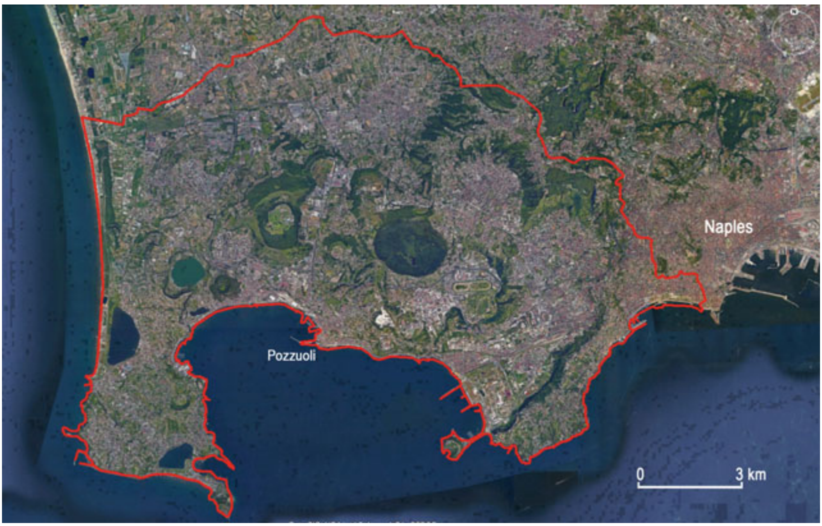


Fig. 4.28 The Red Zone ("*Zona Rossa*") as identified by emergency planning for the Campi Flegrei. The reference scenario is that of an eruption similar to that of the Agnano-Mt. Spina event which occurred about 4,000 years ago in the Phlegraean caldera

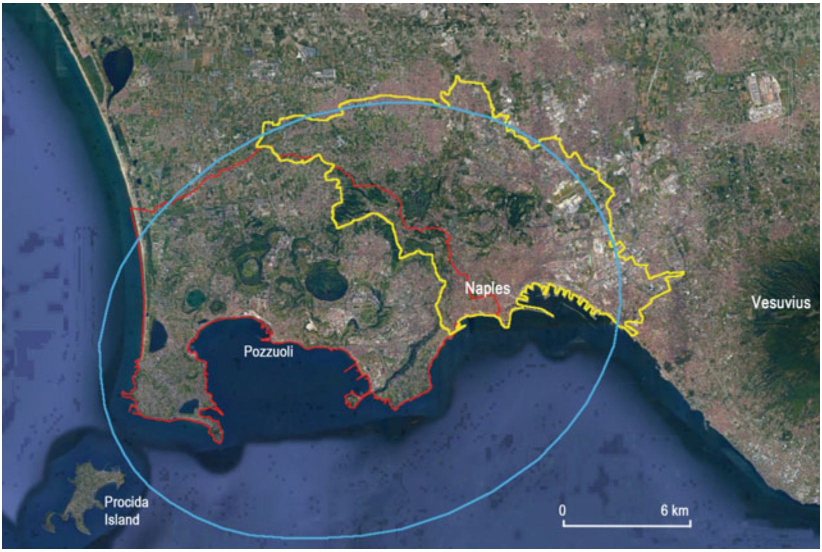


Fig. 4.29 The Yellow Zone ("*Zona Gialla*") of the Campi Flegrei. This indicates the area in which it is possible that substantial ash accumulations may occur, deriving from the volcano's explosive activity. The blue line indicates the approximate area within which there may be accumulations of ash greater than 300 kg/m^2 (probability of 5%) (source www.protezionecivile.gov.it)

acceptable risk. This assessment was made considering that the probability of this event being exceeded by a major energy eruption is less than 5%. The reference event for the Campi Flegrei may be similar to the eruption of Agnano-Monte Spina that occurred about 4,000 years ago just east of La Solfatara.

The Red Zone of the Campi Flegrei, which represents the area at risk of invasion by pyroclastic flows, extends just beyond the limits of the caldera and covers the municipalities of the Phlegraean area and some sectors of western and central Naples. The Yellow Zone, the definition of which is based on recent studies and simulations of the ground level distribution of volcanic ash while taking into account the historical statistics of the wind at high altitude, covers six municipalities and twenty-four districts of the Municipality of Naples. As far as the island of Ischia is concerned, the reference scenario for the preparation of emergency planning is currently being defined. Excluding the Monte Epomeo Green Tuff eruption, on average, the volcanic activity on the island has been characterized by eruptions of small or moderate levels of energy. The scenario to be proposed will have to take into account the peculiar dynamics of the island, the eruptions on which, historically at least, have been closely related to the resurgence process of Monte Epomeo. The latter is also associated with a high gravitational instability, which in the past has generated landslides of enormous proportions, with volumes of several cubic kilometres.

4.8 The Recent State of Neapolitan Volcanoes

The most recent eruption occurring in the Neapolitan area is that of Vesuvius, in 1944. The last eruption in the Campi Flegrei occurred in 1538, while on the island of Ischia the last volcanic event dates back to 1302 (see also Chap. 1). The monitoring of the Neapolitan volcanoes began with the inauguration of the Vesuvian Observatory in 1845, but only in more recent times has this taken on an investigative character focused on the prediction of eruptions. This passage took place in the 1980s when the centre of the city of Pozzuoli, in the Campi Flegrei, rose about two metres and was accompanied by intense seismic activity. At that time the seismic and geodetic surveillance network of the earthquake recording observatory and ground level changes was strengthened. Later, as a result of the enormous technological developments of the last twenty years, the surveillance networks of the Vesuvian Observatory have seen the use of increasingly sophisticated and accurate monitoring methods (Figs. 4.30, 4.31 and 4.32, Appendix E).

The quiescence of the Neapolitan volcanoes, at Vesuvius, in the Campi Flegrei and on the island of Ischia manifests itself in different ways as a result of the different geological and tectonic characteristics and the thermal energy budgets provided by the residual magma located at different depths.

4.8.1 Vesuvius

Before the last eruption, which occurred in 1944, Vesuvius was characterized by open-conduit volcanic activity, which had continued on and off since 1631. With the creation of the Vesuvian Observatory, the first monitoring instruments were placed on the upper part of the volcano. These included the first experimental seismometers, such Palmieri's, installed in 1856 and which actually did not record the waveform but gave only information about the beginning of the earthquake and the duration of the event (seismoscope) (Fig. 4.33). Fundamental historical information concerning the earthquakes that were precursor events to the eruptions

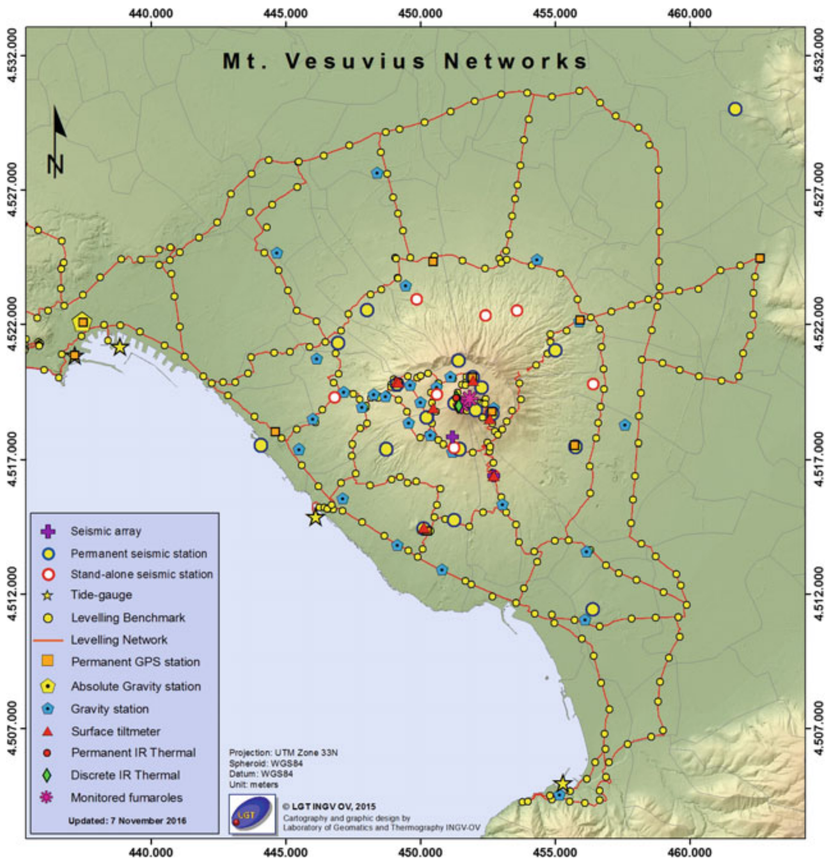


Fig. 4.30 Monitoring network of the Vesuvian-INGV Observatory, currently in operation on Vesuvius (as presented by the Geomatic and Cartography Laboratory of OV-INGV, courtesy of Eliana Bellucci Sessa)

of Vesuvius are incomplete and discontinuous. In fact, at least until the 1960s, the volcano was not equipped with an actual seismic network and the choice to use seismometers in a continuous fashion on Vesuvius depended mainly on the scientific background of the directors of the observatory. With Palmieri, who was a seismologist, more importance was given to the study of earthquakes, while there was no seismic data on the major eruption of the last century, that of 1906. At that time the director was Vittorio Matteucci, a geologist by extraction, who was less

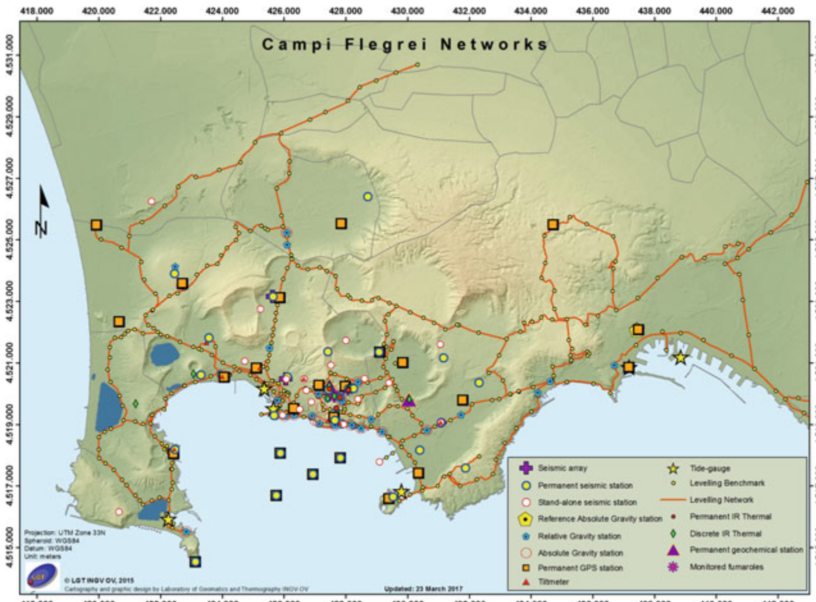


Fig. 4.31 Monitoring network of the Vesuvian -INGV Observatory, currently in operation at the Campi Flegrei (as presented by the Geomatic and Cartography Laboratory of OV-INGV, courtesy of Eliana Bellucci Sessa)

attentive to the study of earthquakes and did not ensure that the seismic instrumentation worked. The seismic activity was however recorded before and during the eruption of 1944, with Giuseppe Imbò as director (Fig. 4.34). This showed the typical characteristics of open-conduit volcanic activity, with earthquake tremors and earthquake swarms, recorded both before and during the eruption. With the quiescence of Vesuvius, the hazard of the volcano decreased, but the exposed value increased enormously as a result of the expansion of the cities around the volcano. This high risk has therefore forced the implementation of monitoring, with new seismic stations that were installed in the crater zone in the second half of the 1960s. The monitoring network was subsequently greatly expanded and is now based on seismological, geodetic and geochemical observations (Fig. 4.35). Since the mid-1970s when the surveillance network of the Vesuvian Observatory began to be potentiated, the volcano has shown weak signs of activity, which mainly consisted of low-magnitude earthquakes located a few kilometres down around the crater axis. Occasional increases in seismic activity have occurred several times in

Fig. 4.32 Monitoring network of the Vesuvian-INGV Observatory, currently in operation on the island of Ischia (as presented by the Geomatic and Cartography Laboratory of OV-INGV, courtesy of Eliana Bellucci Sessa)

recent decades, with small crises such as those of 1978–1980, 1989–1990, 1995–1996 and 1999–2000. The highest energy seismic activity occurred in 1999, when more than 2000 shocks were recorded, with the maximum magnitude event of 3.6 on 9th October 1999. This earthquake sent a strong wave of fear throughout the area around Vesuvius and was clearly felt in Naples and in the south-eastern sector of the volcano as far away as the Sorrento Peninsula. There was heated debate about the dangers represented by Vesuvius following this seismic crisis which, according to some volcanologists, might have indicated the arrival of magma in deep areas and therefore represent a medium or long-term precursor of a possible eruption. However, if moderate changes in the chemical composition of the fumaroles are excluded, no significant changes occurred in the general state of the volcano. It is possible that this crisis was triggered by the diffusion of a pressure front, associated with the arrival of magmatic fluids. This produced an increase in CO_2 (carbon dioxide) and He (helium) concentration measured in the fumaroles.

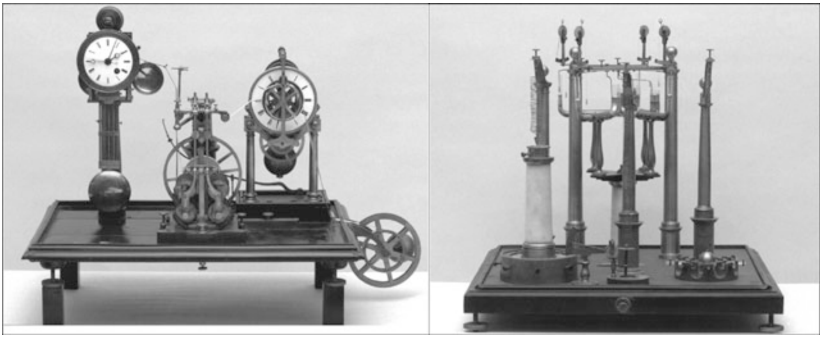


Fig. 4.33 A seismograph created by Luigi Palmieri, made in 1856 and exhibited at the Vesuvius Observatory museum, in Ercolano (courtesy of G. Ricciardi)

On Vesuvius there are on average several hundred earthquakes recorded per year, which have typical features of volcano-tectonic events, with depths that rarely exceed 5–6 km and magnitudes typically less than 2.5. Figure 4.36 shows the Vesuvius seismicity recorded from 1944 to 2009. It would seem that after 1944 the frequency of earthquakes decreased for several years before beginning to rise again around 1964. However, this distribution could have been influenced, at least in part, by the number of seismic stations present around the volcano. In fact, in 1964, a modern Hosaka seismometer was installed at the base of the crater, which may have improved the sensitivity threshold of the seismic network, resulting in an increase in the number of low-magnitude earthquakes recorded. The change in the type of seismicity observed, after 1944, provides important information on the dynamics of the volcano and the hazard it represents. With the end of the eruptive activity Vesuvius has progressively cooled down, leading to an increase in the rigidity of the magma supply system along the crater axis. Among the physical processes involved that then acted on the volcano, the depressurization of the superficial magmatic system was decisive and affected the local stress field, with the prevalence of the lithostatic load on the structure of the volcano itself. This acts mainly along the crater axis, at the point where the weight of the rocks reaches its maximum value. This zone is characterized by strong contrasts in its lateral rigidity, which favour the fracturing of the rocks subjected to stress induced by the load while generating low-energy earthquakes. The seismicity that is localized in the shallow volume of the volcano, down to a depth of 1–2 km, is thus mostly driven by the shear stress induced by gravity. The deepest seismicity, up to about 7 km down, would seem to be related to more complex mechanisms such as the evolution of the regional stress field and the

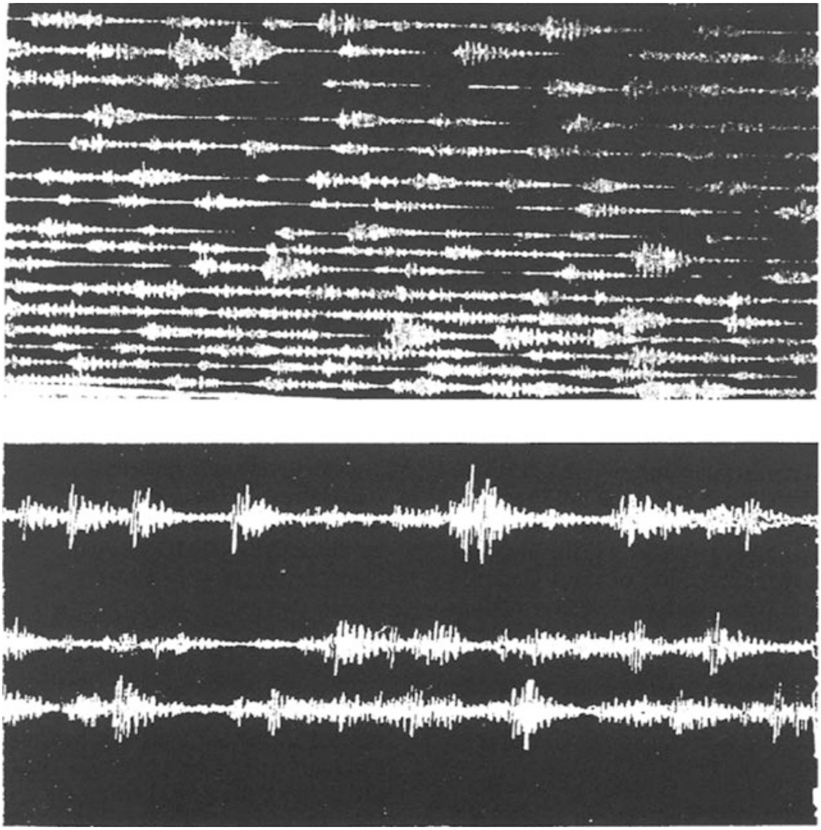


Fig. 4.34 A recording of seismic precursor of the last eruption of Vesuvius' in 1944 (after Imbò, 1954)

presence of fluids that are transferred from the deepest areas of magma supply (Fig. 4.37). In both cases one can note that the seismic activity of Vesuvius is symptomatic of its quiescence, characterized by a progressive cooling of the rocks and by structural adjustment processes within the volcano itself. It is therefore reasonable to assume that the current seismic dynamics of Vesuvius have no direct correlation with its magmatic activity, and that therefore the earthquakes recorded in the last seventy years cannot be considered as precursors of eruptions. A change in the type of seismic events, in terms of depth, frequency, magnitude, and waveform, may instead indicate the reactivation of the deep magmatic system. In this case,

Fig. 4.35 A seismic station, with remote transmission, located on the crater of Vesuvius (courtesy of M. Orazi)

variations in the chemical composition of the fluids emitted by the fumaroles and an increase in their temperature may also be observed. Today Vesuvius is characterized by a weak degassing activity, which is mainly to be observed in the crater area, where some fumarolic emissions persist with relatively low temperatures of between 60 and 70 °C. The fumarole monitoring does not show significant variations in the chemical and isotopic composition, indicating a stable degassing process, without the addition of magma. The source of fluids emitted in the area of the crater would appear to be located at around 3–4 km, probably settling in the levels of carbonate rocks, the top of which were found less than 2 km deep in the Trecase well which was drilled just south of the crater. The deeper fluids, coming from the degassing of the magma source, between 8 and 10 km down, enrich the most superficial aquifers with magmatic gas, and therefore represent an important marker to understand how much of the fluid component associated with the magma participates in the degassing process. An analysis of the long time-series of geochemical monitoring data has allowed the identification of processes that occur with varying frequency. Short-period variations appear to be linked to the processes taking place at shallow depths in the hydrothermal system and that are also affected by the seasonal variation in meteoric waters. Long-term variations are induced by deep changes in the volcano dynamic. In the thermodynamic balance of the volcano, these processes are caused by the transfer of heat from deep areas to the surface. In this regard, the temperatures

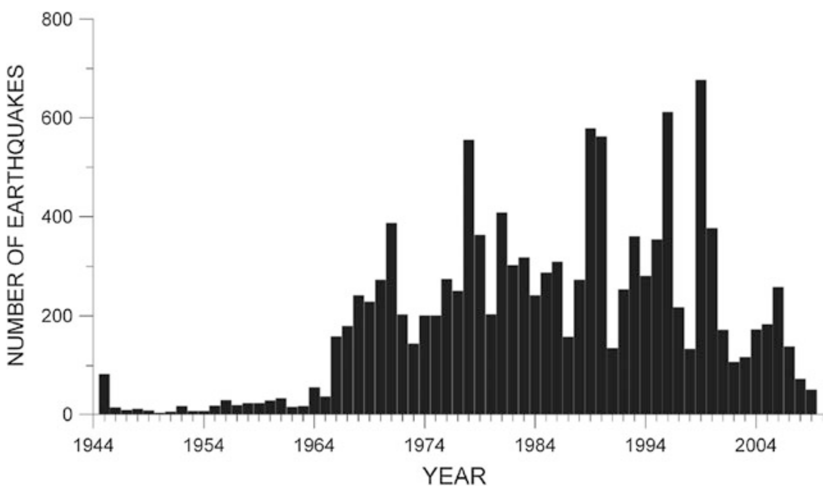


Fig. 4.36 A histogram of the rate of occurrence of volcano-tectonic earthquakes recorded from 1945 to 2009 at the OVO station located on the crater (after Giudicepietro et al. 2010)

measured in the Trecase well, up to 2 km down, exhibit a low geothermal gradient, of less than 30 °C/km, equal to the average gradient found in stable continental areas. In volcanic areas, heat transfer from deep down to the surface typically takes place via rising fluids, which rapidly transport the latent heat accumulated in the magma and surrounding rocks. In this case, as happened for the Campi Flegrei and the island of Ischia, when the fluids reach the most permeable levels in the superficial crust, a hydrothermal system is generated, with typically high temperatures. The low temperatures measured at Vesuvius, may indicate that the most superficial magma system is now completely degassed and that the heat of the deepest source is mainly being transferred by conduction. This latter process is much slower and less efficient than the transport of heat by rising fluids.

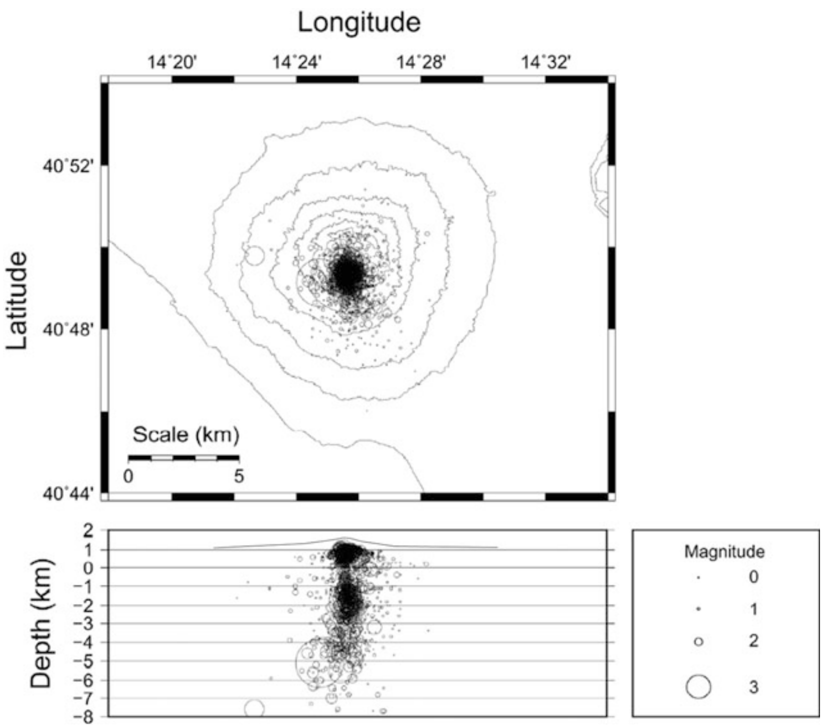


Fig. 4.37 The location of epicentres and hypocentres of the earthquakes recorded on Vesuvius since 1999 (after D'Auria et al. 2013). The seismicity is mainly localized along the crater axis with a magnitude generally not exceeding 2.0

The state of quiescence of the volcano is therefore corroborated by seismic and geochemical monitoring data, consistent with a slow and progressive decrease in temperature and pressure of the magmatic system. This condition is also confirmed by the ground deformation data, which show a general stability of the entire volcanic apparatus with a slight downward trend measured for the crater area.

It seems correct to suppose that in a volcano with a closed conduit like Vesuvius, which has now been dormant for over seventy years, the approach of an eruption produces seismic precursors, even long-term ones, the energy of which can deviate considerably from that released by the volcano up to now. The magma must, in fact, make its way from deep areas, probably around 10 km down, within compact but fragile rocks. This should be causing fracturing of the rocks with noticeable and frequent earthquakes. For this reason, the study and analysis of seismic signals produced by Vesuvius are fundamental for our understanding of volcanic dynamics. The data deriving from geochemical and geodetic monitoring, interpreted together with seismic ones, should therefore provide a sufficiently reliable framework to understand when the volcano becomes close to critical eruptive conditions.

4.8.2 Campi Flegrei

The peculiar feature of Campi Flegrei caldera, as in other calderas around the world, is the continuous uplifting of the ground (resurgence) that here, over millennia, has produced volcano-tectonic dislocations that are clearly visible in some areas such as along the seaside terrace at La Starza, near Pozzuoli. As already mentioned above, the volcanic monitoring of the Campi Flegrei began in the 1970s, when there was a conspicuous uplifting of the ground that, after a period of stasis lasting about ten years, continued with the great bradyseism crisis of 1982–84. Until that time, the focus was mainly on Vesuvius, since the volcanic activity of the Campi Flegrei had been interrupted many years before, during the Renaissance period, with the last eruption in 1538. Evidence for deep magmatic activity was observed, as it still is today, around the Solfatara volcano and in the areas adjacent to it, between Pisciarelli and Agnano. However, the most recent memory of the eruption of Vesuvius in 1944 and its continuous activity over the previous centuries had naturally shifted the attention to the more well-known Neapolitan volcano. When, in the 1970s and 1980s, it was realized that the Campi Flegrei might represent a threat, like Vesuvius, and following the second evacuation of the city of Pozzuoli as a result of the bradyseism crises, the volcanic monitoring of the caldera has been progressively intensified. In those years the study of the mechanisms of large explosive eruptions and the dynamics of pyroclastic flows were deepened, the latter representing the greatest threat to the populations living near active volcanoes. Authors such as Smith in 1960, McCall in 1963, Smith and Bailey in 1968, and Marsh in 1984 were among the first to perform systematic studies on calderas and the mechanisms surrounding subsidence and resurgence, demonstrating that these volcanic systems have different dynamics from central volcanoes. The interest in the study of the caldera was amplified by the fact that the formation of these volcanoes is associated with catastrophic eruptions, which might directly affect very large areas, and which can generate large-scale climatic disturbances. The effects of large caldera eruptions have been compared to those that might be produced by the impact of a large meteorite on Earth. Although these are very rare events, for which we have no human witness accounts, the study of the eruptions forming caldera is crucial for the assessment of volcanic risk. The subsequent investigations on the calderas, have seen the Campi Flegrei as protagonist, not only for its eruptive potential, but because this area is set in a context of high urbanization. The recent history of the unrest occurring in the 1970s and 1980s in the Campi Flegrei was described above, so in this section we focus on what has happened in more recent times and on the monitoring data recorded between 1984 and today. In this period the monitoring network covering the Campi Flegrei was greatly strengthened, particularly through projects financed by the European Community, the Campania Region and the Italian Civil Protection authorities. This upgrading involved the geodetic networks, in particular using GPS to record vertical and horizontal displacements of the ground, the gravimetric network as well as seismic and geochemical networks. This has provided remote data with high spatial resolution, in particular with regard to seismicity and ground deformations. Following the 1982–84 bradyseism the ground of the Campi Flegrei gradually subsided at a rate of about 16 cm/year, between 1985 and 1988, and of 3 cm/year between 1996 and 2003. Later, and until 2005 the ground showed a certain stability. Since 2005, the subsidence trend, which had lasted for over thirty years, has been reversed again, starting an uplift phase within the caldera, centred on Pozzuoli. From 2006 to 2010 the lifting rate recorded by the GPS network was about 1.2 cm/year, then increasing to about 2.5 cm/year from 2010 to 2012 before reaching a maximum of about 5 cm between 2012 and 2013 (Fig. 4.38). The increase in the lifting rate was accompanied by sporadic seismic swarms that in some cases were clearly felt by the population of Pozzuoli, the latter being greatly concerned as these swarms brought to mind the evacuation of Pozzuoli in the 1980s. A further concern of scientists about the state of Campi Flegrei came from the geochemical monitoring data, as the magmatic component of fumaroles increased, together with swarms of earthquakes and the ground uplift. In particular, since 2006, geochemical data may indicate that the hydrothermal system has undergone repeated injections of magmatic fluids. Physical simulations of the observed process show that total injected fluid masses are the same order of magnitude as those emitted during small to medium-sized volcanic eruptions, and their cumulative curve highlights a current period of increasing activity. Despite the physical simulations not being able to reproduce the real nature of the processes occurring at depth and the interpretation of the most recent unrest in terms of hazard remaining ambiguous, the data recorded since 2005 show a clear inversion of tendency with respect to the years 1984–2005. On the basis of the monitoring data recorded and the assessments of Italy's Large Risks Commission, in December 2012 the Department of Civil Protection, in agreement with the Campania Region, deemed it necessary to move from the base level alert (green) to that of attention (yellow). The latter envisages an increase in the monitoring of volcanic phenomena, while the scientists' attention has turned to the interpretation of data to establish how possible scenarios might evolve. In operational terms, therefore, the yellow level does not foresee the involvement of the population in civil protection activities, but greater scientific attention being paid to the phenomena in progress. Post-2013, the ground level at the Campi Flegrei remained almost stable until mid-2015 when it then began to lift at a rate slightly lower than that observed two years earlier. As with the 1982–84 crisis, today it is being noted that the earthquakes typically occur concomitantly with the acceleration of ground lifting, even when small uplifts occur. This could indicate a level of critical stress accumulated in the crust, despite the deformation of 1982–84 having been partly recovered with the partial ground subsidence. Moreover, during the lifting, the rocks, in addition to being subject to pressures close to the breaking limit, are being pervaded by pressurized geothermal fluids, which facilitate sliding along the pre-existing faults, generating earthquakes. These generally occur at depths of between 1 and 4 km and are easily felt by the population when the magnitudes exceed values of about 1.5. The areas in which these can be felt are typically those immediately adjacent to the epicentres, mostly located between Pozzuoli, Solfatara and Agnano. Moreover, from 1970 until today, it has been noted that the deformation of the ground maintains the same shape and, more or less, the same centre of maximum lifting, indicating that the source of pressure is always the same and appears to be located at about 3–4 km depth. If the observed lift from 2005 was brought about by the slow injection of new magma, and if the process were to continue into the future, the physical conditions for an eruption could not occur, which are strongly conditioned by the rheological state of the magma. Basically, the magma would be arriving too slowly in the accumulation area, so that the heat diffusion would be faster than the incoming heat entering the system. In this case, not only are the conditions for rock recasting not necessary, but even the incoming magma tends to cool quickly, with an increase in viscosity. This process inhibits the mobility of the magma itself and its migration to the surface. Vice versa it also favours the increase in pressure within the magma source and the consequent lifting of the ground. This interpretation emerges from recent scientific studies that focus on the role of the rheology of the magma, and therefore of its viscosity, in the eruptive processes and lifting of the resurgent calderas.

This all indicates that the dynamics of the Campi Flegrei caldera seem to be more complex than that of Vesuvius. The observed instability, and the fact that the caldera is in a state of unrest in which it is difficult to quantify a certain threshold of danger (the one that should correspond to the different levels of alert in the emergency plan) renders it very complex to make a forecast in either the short or the long term. Given the uncertainties of the problem, it is useful in this case to consider more than one starting hypothesis, each of which might lead to different hazard scenarios. In this way it is possible to verify the reliability of the starting hypotheses in terms of recorded observables and then define the expected scenarios.

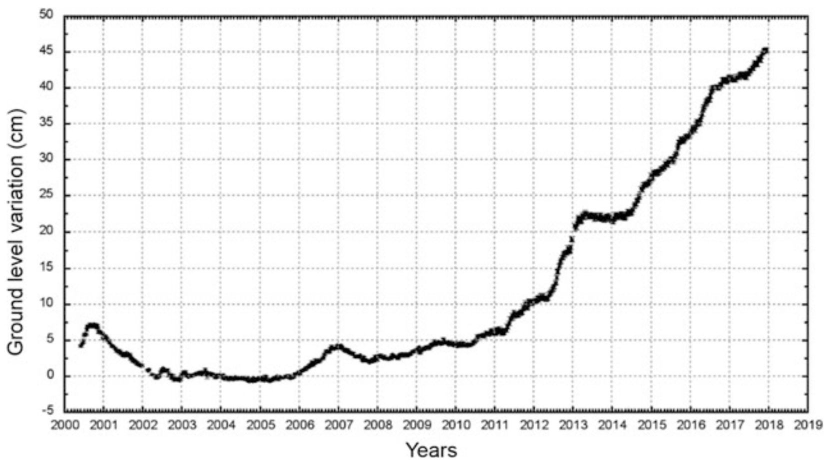


Fig. 4.38 Ground level variation recorded by the GPS station in the centre of Pozzuoli from 2000 through to the present (www.ov.ingv.it)

4.8.3 The Island of Ischia

The monitoring of the island of Ischia has been influenced over the years by its low volcanic dynamics, such that researchers' attention turned mainly to the Campi Flegrei and Vesuvius, characterized by higher risks for the greater number of exposed inhabitants. In recent times however, and in particular following the earthquake of 21st August 2018, the seismic monitoring network has been further enhanced, while the GPS and optical levelling network has been providing information on ground deformations. The main volcano-tectonic phenomenon that has characterized the geological history of the island is represented by the resurgence of Monte Eponemo, which has risen by at least 800 m in the last 55,000 years. The first signs of the inversion of this resurgence are found in submerged Greek–Roman finds along some stretches of the coast, which indicate a general subsidence trend over the last 2,000 years. In fact, the archaeological remains provide valuable information on the variations in the altitude of the coastline, a reference among other things that is heavily used, both in this area and in the area of the Campi Flegrei, due to the presence of numerous sites from the Greek–Roman era. In the northern sector of the island, at Lacco Ameno, at the Terme Regina Isabella, Greek walls from the 4th century B.C and the flooring with Roman walls dating back to the 2nd century A.D. appear below their original levels. There is similar evidence at the springs of Saint Restituta and in the cave of Varulo, where there is a Roman pool that has lowered by about 3.5 m compared to the original floor. Further archaeological evidence of the subsidence of the island is found in Casamicciola, near Punta della Scrofa, where there are some submerged Roman buildings, and in the eastern sector, near the Castello d'Ischia and to the south at Sant'Angelo-Maronti. In general, the remains of the Greek and Roman settlements indicate a lowering of the ground of about 2 m in the last 2,000 years (0.1 cm/year), although in reality subsidence has affected the various sectors of the island in different ways, with variable lowering rates. The first geodetic surveys on Ischia date back to 1913 and showed that the southern sector of the island was tending to lower more than the northern one. In fact, already between 1892 and 1912 Giulio Grablovitz, the director of the old Geodynamic Observatory of Casamicciola (see Appendix D), using the sea data of the measuring station of the Port of Ischia, had already demonstrated that the island's ground was lowering at a velocity of about 3.3 cm/year.

More recently, the deformations and subsidence of the island have been recorded by the tiltmeter network and GPS monitoring (the latter with fixed and mobile stations). The first GPS station was installed in 1999 and the network was subsequently upgraded in 2001, and then subsequently until it achieved its current configuration (Fig. 4.32). At least over the last twenty years, data from the GPS network has shown an average general lowering of the island of about 6.5 mm/year, with higher values in the southern sector. This subsidence trend had been accompanied by very sporadic and very low-energy seismic activity and by powerful degassing activity, with high temperatures, especially in the central-western and southern areas of the island. The seismic silence was interrupted on 21st August 2017 by a magnitude 4.0 earthquake, accompanied by small-scale seismic swarms. The main event caused extensive damages, two fatalities and dozens of injured, and brought back the catastrophic earthquake of 1883 that destroyed Casamicciola to the islanders' memories (for a more detailed description see the section "Volcanic earthquakes and risk" above). The studies of the 21st August 2017 earthquake have shown that the seismicity of the island is associated with a process that is uncommon for volcanic earthquakes, and that does not involve the magma as source of stress. In fact, the lithostatic load of the structure of Monte Epomeo may represent the source of the principal stress that acts on the ductile underlying crust. The latter responds to the volcanic loading with creep processes that can activate the faults located on Monte Epomeo's northern flank. What is more, the continuous depressurization of the geothermal system beneath the Monte Epomeo and the circulation of geothermal fluids may represent potential mechanisms enhancing the occurrence of the earthquakes on the Island.

The geothermal manifestations of Ischia are certainly the most evident sign of the magmatic activity that has affected the island in the past, generating eruptions and lifting Monte Epomeo. On the basis of integrated studies, deriving from geophysical and geochemical investigations, a hydrothermal circulation model has been defined, focusing mainly on the south-western area of the island where the main thermal manifestations emerge (Fig. 4.39). The circulation of fluids seems to occur in two distinct "reservoirs" superimposed at depths of ~ 200 and ~ 1000 m with temperatures of 150 and 270 °C respectively. The ascent and boiling of the deep hot fluids produces a remixing to a significant extent near the coast with water of marine origin in the most superficial reservoir and to a lesser extent with water of meteoric origin. These waters, rich in mineral salts, are used for thermal bathing. The meteoric contribution seems to be more important in the sectors close to the resurgent block of Monte Epomeo. Based on the results of geochemical investigations of the geothermal fluids in the western sector of Ischia, it is clear that the magma source provides the main contribution of gases such as carbon dioxide and helium. Moreover, the geochemical analyses carried out in the last twenty years do not show substantial variations in the composition and concentration of volcanic gases, in accordance with a slow and continuous degassing process that is taking place from a magmatic reservoir located at a shallow depth of around 2 km. In addition, following the earthquake of 21st August 2018, there were no significant variations in the flow and composition of fumarolic fluids. This said, some anomalies were reported immediately after the earthquake, such as the variation in the water level in the geothermal wells and in the flow of certain hydrothermal springs. In the aftermath of the earthquake, some small areas with dried-out vegetation have also been identified, a phenomenon that might be associated with a transient impulse of carbon dioxide along the fractures that border the seismogenic area. In general these observable phenomena can be attributed to variation in the local stress field generated as a result of the earthquake, which acted transiently on the pattern of circulation of geothermal fluids and on the degassing processes.

The earthquake of 21st August, as was already hypothesized for the event of 1883, has shown a substantial underestimation of the seismic risk on the island, where the repercussions of earthquakes, while taking place across a very small area, have the potential to wreak very serious damage (Fig. 4.40). For the event of 21st August in the area of the earthquake, the peak ground accelerations recorded by the Vesuvian Observatory seismic network showed values equal to about 28% of that of the acceleration of gravity (equivalent to a peak ground speed of about 18 cm/s). These values are higher than those estimated by the national seismic

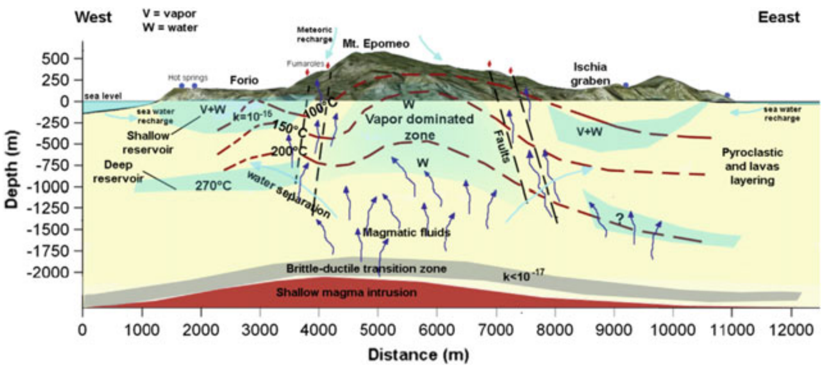


Fig. 4.39 A general sketch of the Island of Ischia's geothermal system. The island is characterized by very high temperatures at shallow depth, particularly in the western and southern sector. A shallow magma intrusion is the main heat engine that is activated by the robust advection of fluids in the rocks. In this diagram are shown the vapour- (v) and water- (w) dominated zones, the permeability value (k), the isotherms (dotted red lines) and the direction of fluid flows (blue arrows) (after Carlino et al. 2014)

classification for the definition of risk on the island and this explains the high levels of damage in Casamicciola due to low magnitude events, where the proximity of the seismic source to the surface (between 1 and 2 km) is the main reason for the damage to buildings. The picture of the observable phenomena on Ischia, in particular the high rate of degassing at the surface and its slow subsidence is consistent with the volcanic quiescence recorded since 1302. The subsidence in volcanic areas is typically associated with low levels of hazard, since the first indicates a depressurization of the volcanic system, without the addition of new magma. Ischia's most superficial magma system, although below the melting point, still contains a large amount of latent heat, which is mainly transported by geothermal fluids. Surface geothermal manifestations should not necessarily be seen as an index of high volcanic danger, especially if geochemical analyses on geothermal fluids do not indicate a contribution of new magma. In fact, geothermal fluids tend

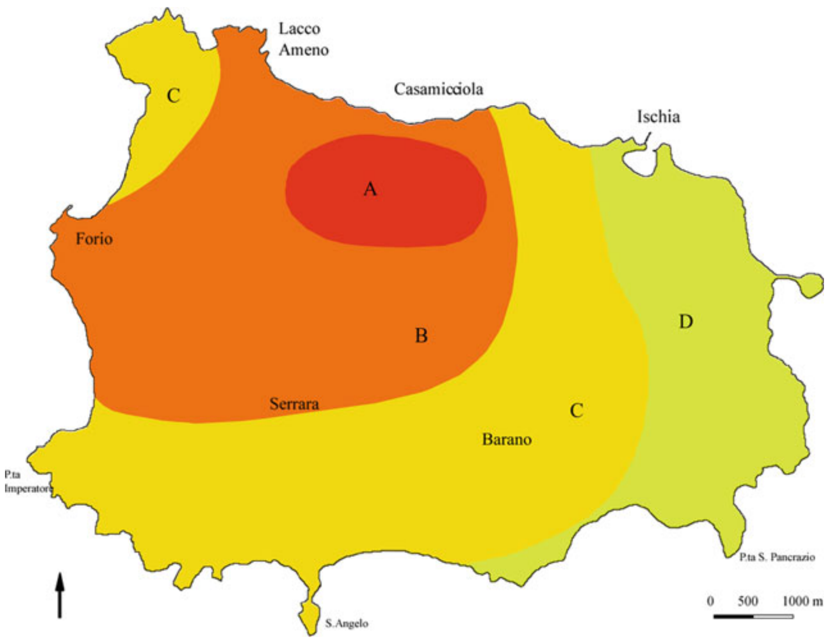


Fig. 4.40 Map of the expected damage on the island from an earthquake in the northern sector with energy comparable to that of the 1883 earthquake. Four zones are shown—A, B, C, D—in decreasing order of damage (from Cubellis and Carlino 2004). The zone A (very high damages) corresponds to the Casamicciola Terme municipality

to transport heat more quickly from the magma source, which is slowly cooled. Although the monitoring data and the geological knowledge of the island are insufficient to obtain an estimate of the volcanic hazard, the observations over the last two centuries, and the volcanological studies on the past 55,000 years of activity indicate that only a reoccurrence of the resurgence would lead to a high risk of eruption. As mentioned above, during the resurgence and subsidence processes, the viscosity of the magma and the rheology of the encasing rocks both play a fundamental role in determining the favourable conditions for the ascent of the magma or its stagnation and for the release of seismic energy. On the other hand, during subsidence, elastic energy is mainly accumulated where there are larger volumes of rock exhibiting fragile behaviour in the northern sector of the island. In this geological context the earthquakes that occur in this part of the island cannot be classified as precursors of eruptions and therefore are not associated with an increase in volcanic hazard.

4.9 Extreme Events

In June 2011, I had the opportunity to participate in a round table discussion in the Philippines entitled "Can Plinian Eruptions be Forecast?" We were taken to visit the areas devastated by the 1991 eruption of Mount Pinatubo that caused the evacuation of 200,000 people from a populated area, but certainly a very different context from urban Naples. The object of the meeting was to try to understand if the precursor signals of large explosive eruptions can, in some way, be discriminated from those that precede small energy eruptions. This was an important topic, since one of the main limitations of volcanology is precisely that of not being able to make predictions about the type of event expected on the basis of the type and energy of its precursors. What emerged clearly from the debate during the six-day round table meeting was the lack of a physical link between the type of precursors and the energy of the eruption. Basically there is no proportionality between the two, and large eruptions are not necessarily preceded by more premonitory energy signals. The limit in recognizing the presence of a possible link is also connected to the non-recording and observation of catastrophic eruptions, which are very rare events, and much less frequent than the small and medium energy eruptions. The record of cases on which a statistical analysis of precursors can be made is therefore limited, but it is also possible that, despite having enough data available for an analysis of this type, no relation is to be found. In fact, the observed or recorded volcanic phenomena cannot be interpreted as simple cause-effect relationships (for example, this type of earthquake will lead to an eruption of a given type), but are an integral part of a system consisting of a very large number of correlated variables and describable only with probabilistic laws. Newhall et al. (2018) have suggested a criterion to identify the candidates for future very large (VEI = 7) eruption but, as the authors highlight, preparation for such-low probability but high-consequence events is difficult to image. Among the most likely candidates to generate such chatstrophic events there are the large calderas, such as the Campi Flegrei. The possibility of very large eruptions is related to a numbers of factors that allow the accumulation of a huge volume of magma at crustal depth and its migration at the surface. Among these factors, tectonics, rheology of rocks around the magma source, magma injection rate and its bouyacny force and the content of crystal in the magmatic sources play a critical role.

As noted above, the loophole of the volcanologists, facing this problem is to adopt an eruptive reference scenario, which is the most probable from a statistical point of view, in the field of medium energy events. This should ensure, in theory at least, that there is no underestimation in evaluating the energy of the next eruptive event. To give an example, in the case of Vesuvius, the conditional probability that an eruption of energy equal to VEI = 3 might occur in the next 200 years—in other words an eruption similar to that of 1944—is 72%. This probability is reduced to 27% for an event VEI = 4, similar to that of 1631, and to 1% for an eruption of VEI = 5, such as that of Pompeii in 79 A.D. Despite the most probable event being that of 1944, the reference scenario chosen for the emergency planning of Vesuvius is that of 1631, which has a lower probability of occurrence. However, since nature is much more complex than statistics, one cannot rule out that even a new Pompeii may occur in the next 200 years.

In both the scientific and political debate on the emergency planning for the Neapolitan area covering volcanic risk, there are those who object that considering the most probable event instead of the maximum (i.e. worst case) scenario is an incorrect choice which does not sufficiently warn the population at risk. For Vesuvius, the worst-case scenario is that of the Avellino eruption 3,800 years ago while, for the Campi Flegrei this was the Campania Ignimbrite eruption (39,000 years ago). In reality the great explosive eruptions have rarely hit the area in a 360° fashion, but typically involve limited sectors but at considerable distances from the eruptive centre, of the order of 20–25 km or more. For VEI = 7 events the pyroclastic flows can travel as far as 80 km. Not having the possibility of knowing for sure which sector of the volcano will be the most badly affected, if we take into consideration a scenario like that of the eruption of Avellino, in theory we ought to evacuate the entire population around Vesuvius within a radius of about 20 km. This would imply the preventive evacuation of at least 1,500,000 people, including the city of Naples. Even more paradoxical would be the case of the Campanian Ignimbrite eruption, which, if taken as a reference case, should foresee the preventive removal of the inhabitants of the entire Campanian Plain, covering a population of at least 3,000,000. Understanding and managing risk in these cases, when dealing with extremely catastrophic but very low probability events is deeply complex. Can the precautionary principle therefore have any meaning when dealing with such devastating but statistically extremely improbable events? On our planet, over the last 10,000 years only a single eruption with VEI $\geq$ 7 (similar to the Campanian Ignimbrite eruption) has been identified, while for eruptions with VEI = 8 only 5 seem to have occurred in the last million years. The low probability of occurrence of these super-events and the difficulty in their physical modelling define a framework for which no human response is sufficient to cope with their possible impact. For the Neapolitan area, emergency plans in these cases are not feasible, since a mass exodus of millions of people is an unworkable scenario. Above anything else, we must be realistic. Where should all these people be taken? How far away should they be taken and for how long? Despite the increased knowledge we have gained on volcanic activity, we are basically unprepared in the face of a major emergency, something that clearly appears in the course of the history of disaster management in our country. The cases of the L'Aquila earthquake in 2009 and the seismic sequence which hit Amatrice in central Italy are a case in point, but these represent only the most recent examples. The management of thousands of displaced persons has always proven complex and burdensome, and the situation has become even more unmanageable as a result of the ongoing nature of the seismic sequence in central Italy for over a year. If the population to move away and relocate to safe areas were to go from several thousand to over a million, how chaotic and expensive would the emergency management become? In addition, volcanic eruptions, once started, can last for many months or even years. In the course of such prolonged volcanic activity, no exact predictions can be made on the progress of eruptive phenomena, and this would imply that, at least in areas closer to the volcano, that the population could not be relocated.

For catastrophic volcanic events in the Neapolitan area, the warning scenarios would be more akin to mass migration than to an evacuation plan meaning the problem is very complex and cannot be managed through emergency plans alone. The fact that the probability of an occurrence of catastrophic eruptions is extremely low does not mean not having to consider this eventuality. The population should not be alarmed, but should be informed as to the real scale of the problem together with information on the possible and realistic solutions while avoiding invoking biblical scenarios. Realistically there is no solution for the defence of the population in the event of an eruption such as that of the Campanian Ignimbrite and the debate on this point becomes more speculative than scientific, because we are speaking about a volcanic phenomenon that has never been observed by humankind and for which we do not know what real evidence, in terms of precursors, might be observable before it happens. We know, in general terms, the impact that ignimbrite eruptions have on the environment and we know that the areas invaded by pyroclastic flows can involve entire regions, but what is the use of delimiting a red area as large as the Campanian Plain? It requires a different approach to the problem, in which the solution, which has as its final result, that of bringing down the levels of risk to acceptable levels, must be independent of the eruptive scenario. Firstly, in the area around the Neapolitan volcanoes, the red areas should indicate those sectors where building is forbidden and instead the change in land use should be encouraged towards activities that are better compatible with the volcanic risk. This solution can only be brought about with appropriate policies and economic incentives by central government. The *red zones* should no longer be considered as static areas, from which the population is simply displaced in the case of an eruption (freezing everything else) but rather constantly evolving territorial realities, where planning, aimed at reducing the risk, is the result of joint interventions by politicians, local authorities, engineers, landscape architects, volcanologists and seismologists. In this context, the population at risk must be an active part of the transformation process and cannot be kept at the margins with respect to the technical and political choices for the future of the area. Such a process would trigger a new "risk economy", understood as finance for activities (with its related assets) compatible with the presence of active volcanoes. The path to be taken is a long and complex one and should foresee large sums of money. Unfortunately, the political and administrative management of the area places strong limitations on this new type of development, since the main responsibilities for land management lie with local authorities, municipalities and Regions that have very limited economic resources. On the contrary, the central state has far greater economic resources, but fewer administrative responsibilities, as it has far less opportunity to operate directly in the processes of mitigation of the areas at risk. For example, municipalities are forced to adapt civil protection plans that take account of their own particular characteristics and requirements, but the state does not guarantee any additional economic income to meet the new planning needs. The result is that the organizational machine stops, and emergency plans often remain only on paper. Naples is certainly a complex reality and not easy to manage in an emergency, and the realities of the suburbs, the towns around Vesuvius and the Campi Flegrei area are even more complex. Such a vast community has never had to confront a large volcanic eruption. On the one hand, the complexity of volcanoes does not allow for the making of deterministic forecasts, and even the eruptive behaviour can change abruptly once the eruption has begun. Otherwise, a very large community exposed to risk must respond adequately to the level of volcanic danger. Whether or not we are able to face a future emergency will depend not only on the capacity of the individual actors participating in the civil protection organization machine, but on the degree of cooperation between all the parties involved, citizens, politicians, scientists, local and state authorities. But all of this must not only take place when the eruption is looming, because in that context it would mean only carrying out an operation to minimize damage and losses in an urban and social context in which the conditions to guarantee the best defence against extreme events are missing. Having considered these limits, every volcanic risk scenario, even the most conservative, will be ineffective in the absence of an adequate political programme. In this context, the simple enlargement of the *red zones* cannot represent an effective method of defence from natural disasters.

4.10 Scientists, Risk and Communication: The Experience of the "Campi Flegrei Deep Drilling Project"

Between 2009 and 2012 I had the opportunity to participate in an international scientific research project, the "Campi Flegrei Deep Drilling Project" (CFDDP), which involved the execution of deep drilling into the Campi Flegrei caldera. The aim of the project was to increase the level of knowledge about the caldera, by directly investigating the deepest rocks, until reaching a level close to the area of possible magma accumulation about 4 km down that fed the caldera system during the last bradyseism crisis (Fig. 4.41). The project, which is not yet officially complete, was conceived in collaboration with other international research institutes and universities, in the United Kingdom, Switzerland, Germany, Spain and the United States, and foresees a long evaluation phase by reviewers belonging to the Committee of the International Continental Scientific Drilling Program (ICDP). The first phase, completed in December 2012, saw the drilling of a pilot well, up to 500 m deep, in the eastern sector of the caldera, within a former industrial area, abandoned at the end of the 1990s and located in the plain of Bagnoli (in the municipality of Naples). The pilot well was necessary to preliminarily investigate the most superficial rocks of the volcano, and define the main physical and chemical characteristics, before drilling the deeper well. The impression I had of the project during the draft phase was very positive, both for the objectives that were set, aimed at the mitigation of volcanic danger in an area with high population density as well as for its innovative aspects (we had advanced into a field that represented a new frontier for

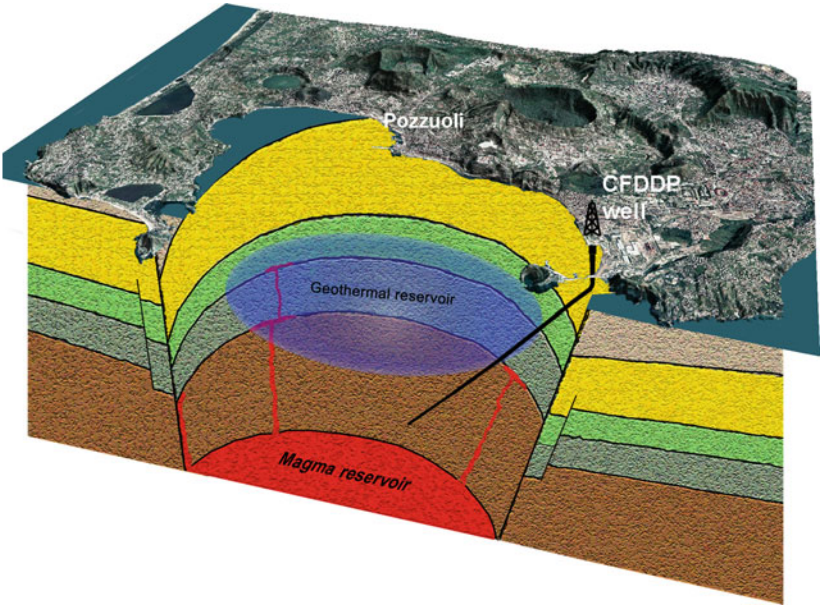


Fig. 4.41 A conceptual sketch of Campi Flegrei caldera with indication of the location and target of CFDDP well

volcanological research that had been never implemented before in Italy but which had already provided excellent results in other volcanoes around the world). The entire research team involved in the project was enthusiastic, but we soon realized that we were dealing with something bigger, which did not strictly concern the scientific community and its internal dynamics. Rather, it was necessary to show the population exposed to risk how science works, the methods it uses and above all the entity of the real risks in tackling a project of this magnitude. In fact, during this process, from the scientific debate on the usefulness and the risks of the CFDDP, opinions emerged which were different from those that had been anticipated and which worried the community and the local authorities. Most of the national and international scientific community agreed on the usefulness of the project and on the nonexistence of the risks feared by the few detractors who belonged to the world of research within the Italian university system. Among the risks voiced was that of the hypothesis of a possible eruption triggered by drilling into the caldera. The debate was very tough, and at times exceeded the limits of the normal scientific dialectic, sparking controversy over the danger of an eruption, which had, as its main effect, that of unnecessarily alarming the population and local authorities. While the controversies were mounting ever higher, in my head it was clear that in the management of the project we had underestimated one aspect, although fundamental, that concerned communication between science and the citizens. For the first time we were directly experiencing what is termed NIMBY syndrome (an acronym for Not In My Back Yard), an attitude that is typically found in the protests against public works or non-public interests that are feared as having negative effects on the area in which they will be built. Nimby-ism also consists of recognizing the objectives of a project as necessary, but, simultaneously, not wanting it to take place in one's own area due to possible negative effects on the local environment. But let us proceed one step at a time. What was important at that critical moment was not to persuade the citizens that their doubts and fears were unfounded but to try to understand the closed attitude of the project's detractors, and in particular those that belonged to the scientific community who, although few in number, with their negative reasoning, were generating strong concerns in the local population. In October 2010 we decided to attempt the path of public debate, inviting both citizens and representatives of the scientific community who opposed CFDDP to the municipality of Bagnoli (the district most directly involved). It was not a very constructive debate, at least not as much as I had anticipated because, even on this occasion, the tone was too polemical and inadequate for scientific comparison and unanimous agreement was not reached on the future development of the project. I noticed that the room in which the debate took place was divided between those who were in favour and those who were against the project, like two football terraces of opposing supporters. In addition to Bagnoli residents, there were local associations, some local politicians as well as members of political parties and movements. After the debate, the opinions of the opposing factions remained essentially unchanged and only a few of those opposed to the project showed themselves open to dialogue. At that juncture, it seemed to me that those who had passively accepted the negative criticism of scientific detractors, or those who had a preconceived idea, could barely change their minds. Citizens who were in favour of drilling were more inclined to dialogue. I attributed this difference to the differing levels of individual knowledge, the positivists being better informed, more interested in the project and with fewer prejudices.

Among the reasons for opposition to the project there was also that linked to the possibility that the drilling would serve to evaluate the thermal potential of the area, facilitating the opening up of a large geothermal power plant for the production of electricity. However, the CFDDP's objectives were quite different, and had no industrial objectives. 2010 was a difficult year for us working on the project. We were plunged into crisis to such an extent that the possibility even arose that the project might be stopped indefinitely, just at the moment when everything was now in position to start drilling. We had the funds and all the necessary authorizations, but we had much of the local media against us and we felt ever fiercer public opinion breathing down our necks. In the swirl of opinions that broke out at that time there was no lack of posts on the social networks and articles in national newspapers by people who, without title or competence on the subject, expressed highly negative judgments. The principle of authority by which scientific communication should abide had lapsed. Reports appeared in the newspapers with headlines such "the Campi Flegrei are like a pressure cooker, dangerous to puncture"; words that, surprisingly, were pronounced even by academics. I wondered how it was possible to make such simplistic statements, without scientific content, after almost 200 years of Neapolitan volcanological research? The confusion was total, and a message was being spread that had nothing to do with the CFDDP's objectives or with the real risks involved in carrying out scientific drilling. However, the problem we were facing did not specifically concern the project, but the scientific world more generally, and above all the ethical position of scientists facing the debate on a sensitive issue such as volcanic risk in the Neapolitan area. Obviously, my objectivity may perhaps be compromised by the fact that I was involved in the project, and this is precisely the point. How reliable are the opinions of researchers who may not have an objective view of things, because they are involved personally and in different ways in relation to the issues they have to deal with? It is essential to understand this, because the topic of volcanic risk, which involves millions of people in the Neapolitan area, must be tackled through paths in which the judgment of scientists must be kept separate from personal or academic interests. To define more precisely what constitutes scientific misconduct we first of all need a better understanding of how science really works. I refer hereinafter to some of the fundamental precepts that scientists should follow for an ethically correct conduct, as described by David Goodstein (2010) in his essay, "*On the facts and fraud, cautionary tales from the front lines of science*":

- a scientist should never be motivated to do science for personal gain, advancement, or other rewards;
- scientists should always be objective when using data for different purpose;
- scientists must never believe dogmatically in an idea or use rhetorical exaggeration in promoting it;
- scientists must be an open book, not an acquired skill;
- scientists should never permit their judgments to be affected by authority. For example, the reputation of the scientist making a given claim is irrelevant to the validity of that claim.

It is not for me to judge whether, in the debate on the risks of CFDDP, scientists were able to maintain ethically correct conduct (according to the principles set out above), but I did not find any sustainable scientific motivation, among those used by the detractors of the project, to halt the drilling. For example, the cases of incidents that had occurred during drilling in other parts of the world were reported to the public to demonstrate the risk of CFDDP, episodes that, however, had nothing to do or with what would be carried out during the drilling of the Campi Flegrei caldera, nor with regard to the geological context of the area. First of all was the false idea that drilling could generate earthquakes. But in many statements, including some of those coming from the academic world, the detractors failed to point out that it is not the drilling that generate earthquakes, but the injection of large volumes of fluids into the wells, thus completely confusing public opinion in understanding cause-effect phenomena. The example repeatedly cited and reported by the media was that of Basel in 2006, where, in the course of a geothermal project (Enanched Geothermal System) high pressure water was injected into a well to cause fracturing and increase the permeability of the rocks. This represents a system used to increase the productivity of geothermal plants. The release of pressurized water into the rocks caused an earthquake of magnitude 3.4, in a densely inhabited area. Even if the drilling was scientific in the Campi Flegrei, and did not foresee any industrial operation within the well, it was very difficult to make the public understand that there was no risk of inducing earthquakes. The same strategy was used to suggest the risk of an eruption. In this case the example of the Lusi volcano in Indonesia was reported, where it is suspected that industrial drilling carried out in 2006 caused a giant emission of mud, which covered entire villages nearby, causing the evacuation of thousands of people. In this case as well only partial news was disclosed, because it neglected to focus on two important facts (i) the uncertain correlation between the mud eruption and the drilling, and (ii) the completely different geological context in which the disaster occurred. This last point is particularly important, because mud volcanos have different dynamics from canonical ones and what happened in Indonesia, could never happen in the Campi Flegrei. For further information, see the following works: (Mazzini et al. (2009, 2012); Manga (2007), Davies et al. (2008) and Inguaggiato et al. (2017)). The declarations—that continued to spread on social networks and newspapers—became increasingly catastrophic, sometimes at the limit of the paradoxical, such as to seriously worry the municipal administration of Naples, which had issued clearance for drilling. The idea that the CFDDP had to be stopped because of the precautionary principle was allowed to pass. The climax was reached on 6th October 2010, when the national newspaper "*Il Mattino*" led with the front page title: "If you touch the volcano Naples will explode" (Fig. 4.42). At that time the

Mayor of Naples, Rosa Russo Iervolino, in agreement with her ruling council, officially decided to block the project, while awaiting new clarifications on the real risks to the population. It was at that point that a short circuit in communication was generated. The requests of the municipal administration of Naples were brought to the civil protection authorities, which, not having the scientific skills to study a problem of this kind, turned to the National Institute of Geophysics and Volcanology, that is, to the body that had promulgated and jointly financed the CFDDP. And here again the principle of authority was allowed to slip, because the project had already been evaluated by the major experts in the field, belonging to the ICDP committee, through a long process of scientific review. An infernal loop was created from which it seemed all but impossible to emerge. In view of the fact that it was not possible to find a team of experts who could re-evaluate the project by bypassing the opinion of the ICDP, the only solution was to convince the municipal administration of Naples that the drilling in the Campi Flegrei not only would not lead to a risk of eruption, but on the contrary would have been useful to better understand the behaviour of the caldera. With the use of appropriate sensors, drilling would also allow scientists to perform a deeper monitoring of seismicity and deformations, filtering out the disturbances that normally occur on the surface due to human activities. But as we had already experienced over the previous days, it seemed very difficult to obtain a change in direction from the municipality of Naples, because the (by now) inculcated idea of the dangerous nature of drilling led non-industry experts to be excessively cautious. We realized that it was not easy to explain why there would be no reason to fear an eruption. For example, we had carried out drilling in other volcanic areas, which had yielded interesting and sometimes surprising results, without any risk of eruption. The most dramatic case concerned the drilling performed in Iceland as part of the Krafla project. In June 2009, in the course of geothermal drilling, a bag of rhyolitic magma was unexpectedly encountered at a depth of 2.1 km. Although the technicians and scientists working on the project were not prepared for such a scenario, there was no risk of eruption. On the contrary, tests were performed to evaluate the electric power that could be extracted from the well, which was about 40 MWe. Iceland is the only country in the world that is self-sufficient in renewable energy resources, using only geothermal and hydroelectric power.

The only precedent, besides the Krafla, is that of the drilling of the geothermal field of Puna in Hawaii in 2005. In this case the magma was encountered at a depth of 2.4 km, but without any consequence, if not that of using the well up at a depth of 2.1 km instead of up to the point where the magma was detected. However, we also had to explain from a scientific point of view why we were so confident in supporting our reasons surrounding the safety of the project. This meant

IL MATTINO NAPOLI

Direttore: Virman Cusenza

06-OTT-2010

Alla vigilia dei carotaggi ai Campi Flegrei l'allarme di Nature, autorevole rivista scientifica Usa

«Se toccate il vulcano Napoli esplode»

«Bucando il magma ci sarà un forte pericolo di eruzione e terremoti»
I tecnici del progetto: nessun rischio

Allarme internazionale sul progetto di perforazione dei Campi flegrei per ottenere nuove fonti di energia: attenzione, c'è il rischio di innescare reazioni a catena, il vulcano potrebbe esplodere. A lanciare l'Sos due media americani, *Popular Science* e l'autorevole *Nature*: il primo con un articolo di Clay Dillow invita i napoletani «a trattenere il respiro» mettendo in guardia contro la possibilità che la trivella intercetti del magma sotto alta pressione perchè - spiega il giornale - teoricamente si potrebbe provocare una eruzione. E *Nature* non è da meno: nel mirino sempre il magma che secondo la rivista potrebbe causare esplosioni o una serie di piccole scosse di terremoto potenzialmente molto pericolose. Il responsabile del progetto, Giuseppe De Natale, ribadisce però le rassicurazioni già fornite in passato: non c'è nessun pericolo, la trivella non procurerà danni.

> Barbuto in cronaca

L'esperimento, l'allarme

«Attenti, se perforate la terra il vulcano esploderà»

Dubbi dei media internazionali alla vigilia dello scavo nei Campi Flegrei. I tecnici del progetto: nessun pericolo

Paolo Barbuto

Allarme internazionale. Tra qualche giorno scatta ufficialmente il progetto di perforazione dell'area vulcanica dei

no e i dubbi sulla sicurezza». L'articolo spiega con precisione tutto quel che avverrà con le operazioni di trivellazione che prenderanno il via a Bagnoli, fa una ricognizione storica dell'attività

fondità di 2.100 metri».

Dal mondo scientifico arrivano suggerimenti ad allontanare il campo di ricerca rispetto alla città. Bagnoli è praticamente dentro Napoli e un

Fig. 4.42 The title of the front page of "Il Mattino" national newspaper, published on 6th October 2010: "If you touch the volcano Naples will explode". The news is related to the concern of people about the project of drilling the caldera of Campi Flegrei

introducing concepts such as magma rheology, supercritical fluids, rock mechanics, and so on. This was about passing messages that were not easily absorbed by non-professionals. Although it seemed we were always stuck at the starting point, politics came to meet us this time. The municipal elections which took place in May 2011 saw the surprise election of a new Mayor for Naples, Luigi De Magistris, young and enterprising and with a more open mind than the previous and more conservative administration. I immediately asked for a meeting with the newly-elected Mayor, to explain the reasons and objectives of the CFDDP. I still remember that meeting very well. It was brief and informal, but I managed to summarize almost everything I had foreshadowed in my mind and left a technical report that explained in more detail what we had discussed. I was sure that soon the project would start again. The response of the Mayor, who gave the clearance to start drilling, was not long in coming. For me it was a small victory, but it was not personal, I was satisfied because the reasons in favour of scientific research had prevailed over populism. In July 2012 the shipyard near Bagnoli was ready, and the first phase of the project began, with the drilling of the pilot well that reached a depth of 500 m. The operations were performed in two steps, the first in July and the second in December (Fig. 4.43). We finished that year on a high point when the auger stopped at the programmed depth of 500 m. The second phase of the project, which involves drilling down to about 4 km is still at the planning stage and we do not know if and when it will start. New funds will be needed, new authorizations will have to be obtained and the aspect of communication with the population and local authorities will have to be better addressed.

Beyond the scientific results that the CFDDP has produced up until now, the experience itself has served to touch on the problem of communication between science (and scientists) and citizens. The language of science has its codes and its rules, and demonstrations of facts always take place through experimental verification. This is the first limit when dealing with Earth Sciences, the theses in which, in many cases, cannot be verified experimentally. The uncertainty of many

Fig. 4.43 Drlling operations of the pilot hole (December 2012) at Bagnoli site during the CFDDP project (photo C. Serio)

problems, such as the prediction of eruptions, makes it necessary to be as transparent as possible when explaining the real limits of scientific research in this field to the public. Clarity is fundamental and when we are not clear, we are necessarily subject to negative popular judgment. On the contrary, in the hard sciences, like physics, scientific data cannot be subject to popular validation and even if 90% of the world said that the Sun was going around the Earth, this opinion would have no value, because the data incontrovertibly shows the opposite. In volcanology it is not so, due to a lack of constituent equations that solve complex systems, so that the indeterminacy of problems can give rise to heated debates, with adverse factions standing in opposition to one another with no one being able to deny the other's position without presenting an experimental fact. The short circuit is born when someone with no title to do so in the debate is allowed to enter the debate. This is therefore the control system that often fails today. Before the advent of the web era, when we had to look up a scientific fact we used bibliographic references, written texts and scientific literature, which ensured that the source of the news was linked to a verification system (peer review) or at least came from people who were entitled to intervene on specific topics. Today, most people, certainly those outside the scientific community, have internet research as their primary source of their information. I do not want to send this instrument to the gallows, which, if used following careful criteria, is a very useful research aid. But there is also the other side of the coin. The internet has changed things, because scientists and researchers are placed on the same level as those who do not do the job. I'm not talking about a social level, but about a cultural one, and we cannot accord the same weight to statements that come from the world of science when compared to those that come from people who are culturally unprepared to express themselves on certain topics. Moreover, opinions are one thing and facts are another. I may disagree with the technological interpretation of a given scientific discovery but not with the fact that that discovery derives from repeatable and verifiable experimental data. From this point of view, the internet has flattened everything, mixing facts and opinions into a single cauldron. A few years ago, before his death, the great Italian writer and philosopher Umberto Eco (1932–2016) was asked to give an opinion on the internet; he replied with these words: "The internet? It gave idiots the right to speak. In the past they only talked in the bar and they were silenced immediately". Perhaps this opinion is a bit strong but summarizes the problem well. In the debate on the CFDDP there was no shortage of speeches by all-rounders, and even in the research and academic world the topics discussed were greatly exaggerated and sometimes oversimplified in an attempt by everyone to validate their thesis and obtain a greater effect up on public opinion. These positions were opposed to those of other, more moderate ones, who tried to pursue a less inductive method to demonstrate the validity of the project. Particular cases, such as that of the Lusi Volcano, could not be considered as establishing a universal law. A certain diffidence towards science was fuelled by the social media networks, but in general a picture emerged in which the communication crisis that science finds itself in was understood. The theme is important, because it involves the research world when the choices of the scientific community interfere at different levels with the life of citizens. But it is necessary to believe in science, because the alternative of not trusting it is a very dangerous road to undertake. From this point of view science is not democratic and while the ideas or theses can be carried forwards by everyone, these have no value if they are not supported by experimental data. In this case the ethics of scientists play a huge role in the evolution of knowledge towards the truth borne out by the facts.

4.11 Final Remarks

In this journey amidst the Neapolitan volcanoes, some of the relationships between the eruptions and human activities have emerged and how the former have influenced the development of the towns around the volcanoes and the demographic and social evolution of the populations exposed to risk. In complex societies such as that of Naples, characterized by a historical stratification with ancient roots, the relationship between humankind and the volcanoes has changed progressively over time. The transition from myth to science takes place slowly and progressively and during this cultural transformation, accompanied by demographic growth, people's attention has shifted from the observation of the natural phenomenon explained in an Aristotelian key until at least the 17th century, to the study of the process in terms of Earth dynamics and the risks for populations living in areas exposed to potentially disastrous natural phenomena. More recently, in-depth research into volcanology and seismic investigations has been conditioned by the need to respond to the security requirements of populations exposed to these natural hazards. In the course of this historical and cultural development, Naples and its surroundings represent an emblematic arena, because here we have all the ingredients that have determined the advances in volcanology and seismology including the presence of active volcanoes, areas with high seismicity, historical stratification covering more than 3000 years and the birth of important scientific institutions together with population growth in hazardous areas.

To this one can add some important facts that came to place the entire area at the centre of the attention of volcanologists and archaeologists worldwide, including the discovery of the ancient cities of Pompeii and Herculaneum buried by the eruption of

79 A.D. and the discovery of the letters of Pliny the Younger recounting the event. This huge historical baggage and the memory of past events seem not to have served as a warning to the population, which, during the post-war period and with the quiescence of both the volcanoes and the public institutions, has continued to expand settlements into areas that have been hit repeatedly by eruptions over time. At the same time, there has been an increase in the scientific knowledge surrounding volcanoes and the physical processes that regulate their behaviour, but without yet being able to furnish exact eruption forecasts. On the other hand, the strengthening of the civil protection machine has brought enormous progress in the management of emergencies, although the political management of the central State in the reconstruction or reconversion of the damaged areas (especially following recent seismic events along the Apennines) has very often been affected by enormous delays, planning errors and the absence of foresight in reconsidering or conserving the localities destroyed. Beyond the numerous limitations that exist in the management of natural disasters, what is clear is that the current development paradigm contrasts strongly with the area's geological reality. In some cases the landscape has been transformed to such an extent as to have become an entity in itself, completely separate from natural reality, where the prediction of those geological elements, from which the origin of the places is well defined and has brought about an abstraction of the areas' identities and a loss of memory of the volcanic events of the past. Yet the eruptions are an integral part of the story of Naples and its surroundings and if you look today with more attention at Nature's more dynamic elements, with their continuous changes and transformations, it is clear that, sooner or later, the volcanoes will return as protagonists in the city's history. Perhaps in no other place in the world there is such a close link between humankind and volcanoes and between these and the historical events that, since the area's colonization by the Greeks, have marked the temperament of the Neapolitans.

The strong contradictions inherent in the character of the Neapolitans, also reflected in the city itself are also inherited from a life lived between "God and Satan", as Goethe stated in his "Journey to Italy" (1816–17), referring to the terrible nature of Vesuvius set against the beauty that surrounds it. The fact that in the era of the Grand Tour Vesuvius was such a major attraction for travellers in Europe brought about the opening up of Neapolitan society towards that of Europe, without however taking advantage of the cultural experience that should have led to an alternate development of the volcanic areas, based precisely on the responsible use of the resources that Nature has so lavishly endowed us with.

Volcanology therefore remains a central topic in the history of Naples and today the topic of volcanic risk must become the occasion for serious discussions, both within the scientific community and outside it. Researchers working on the

Neapolitan volcanoes have a difficult task because they must guarantee the reliability of eruption predictions in an area in which more than 1,500,000 people are potentially exposed to volcanic risk. Research also has the task of disseminating its results to the world outside, of keeping its citizens correctly informed, of incentivizing the culture of risk, and improving its perception. Then there is the cultural, historical and archaeological heritage that we have inherited, whose formation is intertwined with the activity of volcanoes and with devastation, but also with the benefits that come from it such as the fertility of the soil and thermal springs. This risk and resource have given these places an indelible cultural imprint. In the Neapolitan area the volcanological itinerary is therefore a journey back into its most intimate past (and on how its future may turn out to be) that does not only involve Earth Sciences, but also Archaeology, Anthropology, Sociology, Urban Planning and many other fields. Many stories and events of Naples can never be read using the correct interpretive key without taking into account the volcanoes. To those want to retrace this itinerary, I hope you have a great trip!

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Appendix A

A Quick Volcano Tour: Vesuvius and Surroundings

From the top of the volcano a 360° view of Campania Plain and surroundings, allowing the observer to interpret the main geographical features of the surrounding area. The above picture shows the landscape looking south from the crater that is open towards the Gulf of Naples. The Gulf is bounded by Punta Campanella and the Island of Capri (to the southeast) and the by the Island of Ischia (to the northwest). The western part of the city of Naples lies within the Campi Flegrei caldera. The two sectors that border the Gulf have different geological genesis, the south-eastern one being formed by carbonate rocks (the Lattari Mountains) while the north-western sector is volcanic in nature (Phlegrean district). The plain between the Lattari Mountains and Vesuvius itself has been filled by volcanic deposits and alluvial material laid down since the Holocene, the carbonate structure having sunk towards the northwest to a depth of about 2 km beneath Vesuvius. (photo A. Fedele)

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A view across the rim of the Mt. Somma caldera (red line) that surrounds the Vesuvius crater (view from the crater). The grey strip, close to the base of the rim, is the lava flow from the last eruption which took place in 1944. Nowadays it is covered by a dense stratum of *Stereocaulon vesuvianum*, a lichen typical of this volcanic area. Following the trails within the Vesuvius National Park it is possible to walk within the valley lying between the Vesuvius crater and the caldera rim of Mt. Somma (the *Valle dell'Inferno*). Along the caldera rim it is possible to observe the intrusion of sub-vertical dikes which fed ancient activity of the volcano (photo A. Fedele)

A sub-vertical dike outcropping along the flank of the caldera rim of Mt. Somma (photo www.cainapoli.wordpress.com)

A view of the *Valle dell'Inferno* (Hell valley) lying between the Mt. Somma caldera and the Vesuvius crater. The lava flow produced during the last eruption of the volcano in 1944 is easily recognisable (photo www.cainapoli.wordpress.com)

The spectacular piling up of lavas inside the crater, erupted during the last period of activity of Vesuvius. The present shape of the crater is the result of the last eruption which took place in 1944. From 1631 to 1944, the crater was repeatedly filled by lava, forming a lake to the brim, which sometimes overflowed down the crater's flanks. (photo A. Fedele)

Pyroclastic flow deposits derived from older explosive activity of Vesuvius, outcropping along the Lagno Macedonia, on the flank of Mt. Somma. The term “*lagno*” denotes an ephemeral water channel incision which is a typical feature of the Mt. Somma volcanic edifice. Along these channels one can examine the most interesting stratigraphic sequences of the ancient volcanic activity (photo S. Carlino)

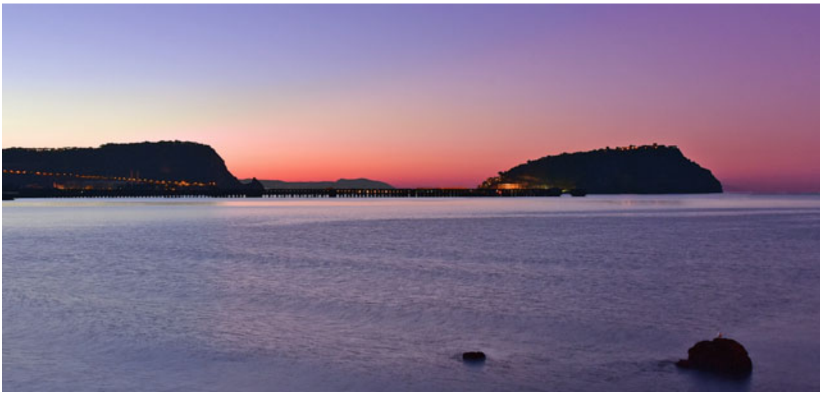
The Santa Croce Church, in Torre del Greco. The construction of the original building, of which only the bell tower remains, was completed in 1740 but was, in fact, partially buried by the lava flow of the 1794 eruption and only the bell tower was saved. In 1827 the Church was rebuilt in a different (neoclassical) architectural style when compared to the older Baroque building. The unusual final configuration is a building with a bell tower lower than the Church itself, below which one can see the ruins of the original structure. (photo A. Fedele)

A view of the steep southeast flanks of the Penisola Sorrentina (Sorrento Peninsula) from the Lattari Mountains. This carbonate structure separates the volcanic area of Vesuvius and the Gulf of Naples (on the right hand side of the picture) from the Gulf of Salerno (on the left). (photo www.cainapoli.wordpress.com)

If you are tired of travelling around Vesuvius and particularly if you are hungry, you should have a break to taste one of the specialities of this area: *baccalà* (salted codfish). The municipality of Somma Vesuviana, in the northern sector of the volcano, is definitely the best place to try this local delicacy, the town being very famous for the manufacture of *baccalà* (photo www.ecampania.it)

Appendix B

A Quick Volcano Tour: The Campi Flegrei and Their Surroundings



A view of the western part of Naples that lies within the caldera of the Campi Flegrei. On the right side lies the Island of Nisida which represents the eastern limit of the Gulf of Pozzuoli. On the left side we can see the Posillipo hill, the eastern limit of the caldera. In the foreground one can see the jetty of the old Bagnoli industrial site which is now used to provide a beautiful walk and view of the Gulf while in the background you can make out the Sorrento Peninsula. (photo A. Fedele)

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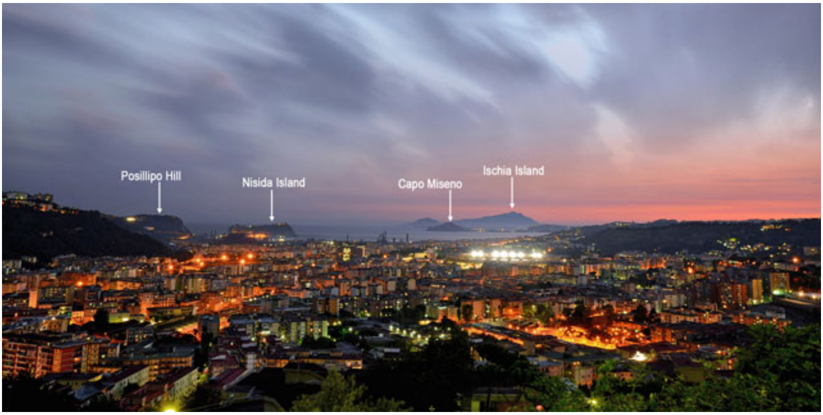

In the foreground is a view of the western part of Naples which includes the neighbourhoods of Fuorigrotta and Bagnoli, located within the caldera of the Campi Flegrei. In the background one can see Capo Miseno (the western limit of the Gulf of Pozzuoli), the Island of Ischia (the western limit of the Gulf of Naples), the island of Nisida and the Posillipo Hill (the eastern limit of the Campi Flegrei caldera). (photo A. Fedele)

A view of the western part of the caldera of the Campi Flegeri from Monte Nuovo. In the foreground lies the lake of Lucrino along the coast between Pozzuoli and Bacoli and, in the background, Monte di Procida which represents the western boundary of the caldera together with the Island of

Ischia which is dominated by the towering structure of Mt. Epomeo. (photo A. Fedele)

A beautiful view of the Capo Miseno beach from Monte di Procida. The beach is crowded during the spring and the summer seasons. Otherwise, the climate here is pleasant throughout the year and the site is ideal for autumn and winter walks and bathing. The beach is separated from the beautiful fisherman village of Bacoli by the Lake Miseno. Nice places to visit include the Capo Miseno volcanic feature and Miseno's natural harbour. In the background lies the town of Pozzuoli (on the left) and the Posillipo Hill (Naples). (photo A. Fedele)

The harbour of Miseno and the lake of the same name in the foreground. The natural inlets and the morphology of the area was created by the phreatic and phreatomagmatic eruptions that occurred within the caldera between 35 ka and 10.5 ka ago. In the background lie the Gauro crater, the Monte Nuovo crater and the Baia Castle. (photo A. Fedele)

The old fisherman's harbour of Pozzuoli, beneath the Rione Terra. Nowadays, the harbour shows the signs of the bradyseism (or uplift) that has occurred in recent times. As we can see from this picture, the dock level has been uplifted and the consequent drop in sea levels makes the docking of boats difficult. A number of stepladders have had to be placed to alleviate this problem. (photo A. Fedele)

Further evidence of the recent bradyseism crises (1970–72 and 1982–84) can be also identified around Pozzuoli's Ferry Boat Harbour. The highlighted feature of the dock was the actual level prior to 1970 but following more than 3 m of uplift, a new dock had to be constructed to allow the boats to dock. On the level of the old dock many mooring bollards are still visible (red square). (photo A. Fedele)

The seafaring tradition of Pozzuoli remains strong and very visible in the faces and the day-to-day gestures of many people. In the town you can buy fresh fish from the many fishing boats that dock in the port. But there are also those who, perhaps tired of sea-going, entertain themselves by building the boat of their dreams in miniature. This photo was taken close to the old fishing port beneath the Rione Terra. (photo A. Fedele)

The *Piscina Mirabilis* ("The Marvellous Swimming-pool") is one of the most incredible archaeological sites of the Campi Flegrei district and represents the largest water cistern ever built by the Romans. It was used to supply the ships of the Roman Naval Fleet, the *Classis Misenensis*. The cistern is located in the centre of the village of Bacoli and was entirely excavated in the tuff of the hill next to the port and is located approximately 8 m above sea level. The structure is 15 m high, 70 m long and 25 m wide with a capacity of 12,000 m^3 with the water being taken from a series of small tanks dug on the terrace overlying the cistern using hydraulic machines and channelled from here towards the port. The walling was created in *opus reticulatum* and, like the pillars, is covered in a waterproof material. A series of openings along the top of the sidewalls and the upper wells themselves were created to provide lighting and aeration of the environment. The *Piscina Mirabilis* constituted the final tank along one of the main Roman aqueducts, the Augustean Aqueduct which carried water from the springs at Serino a distance of 100 km to Naples and on to the Campi Flegrei. Part of the ancient cistern is open to visitors. (photo www.c.f.facebook.com/puteoli)

Appendix C

A Quick Volcano Tour: The Island of Ischia

The Mt. S. Angelo peninsula (in the southern part of the island) is made up of a lava dome at its base and is covered with a sequence of pyroclastic deposits that filled the blocky top of the dome. This volcanic centre has created a minor inlet which nowadays hosts a small harbour used by local fisherman and is certainly one of the most beautiful and charming on the island. (photo A. Fedele)

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A sequence of pyroclastic surges outcropping along the western side of Mt. S. Angelo peninsula (in the southern part of the island). This volcanic deposit was formed during hydromagmatic activity (between 19 ka and 20 ka B.P.) and consists of pomiceous lapilli, bombs, ash and lithic. (photo A. Fedele)

The discordance (red line) between the old trachytic lavas (95–100 ka B.P) and pyroclastic surge deposits outcropping at the base of the Mt. S. Angelo peninsula. (photo A. Fedele)

The small settlement of S. Angelo (southern part of the island). If you are looking for good food and leisure, this is your place (photo A. Fedele)

The Castello d'Ischia promontory is located in the eastern part of the island. It is a typical alkali-trachytic exogenous dome formed about 130 ka B.P. The Aragon Castle was built on the dome during around 474 B.C. In 1441 Alfonso V of Aragon connected the rock to the island, a stone bridge replacing the old wooden one, and fortified the walls to defend the inhabitants from raids by pirates. Nowadays it is accessed via a tunnel with large openings which let the light enter. Along the tunnel is a small chapel consecrated to John Joseph of the Cross (San Giovan Giuseppe della Croce), the patron saint of the island. A more comfortable access is also possible using a modern lift. After arriving outside, it is possible to visit the Church of the Immacolata and the Cathedral of Assunta. The first was built in 1737 on the location of a smaller chapel dedicated to Saint Francis, and closed after the suppression of the Convents in 1806 as well as the nunnery of the Clarisses. (photo A. Fedele)

A fisherman's life at Ischia Ponte (in the western part of the island). (photo A. Fedele)

A huge block of Mt. Epomeo Green Tuff lying on the southern slope of the mountain itself. These blocks frequently outcrop along the on-shore and off-shore areas of the southern part of the island and arrived during huge debris avalanches down the slopes of Mt. Epomeo. But the people of Ischia are “eccentric” and here someone has decided to build a restaurant that stands, literally, “on the block”. (photo A. Fedele)

The little bay of Sorgeto, located in the southern part of the island. Here you can find one of the treasures of Ischia as the bay is characterized by a rocky beach with sea hot springs that allow for a relaxing bath, even during the winter months. (photo A. Fedele).

A beautiful view northwestwards from the top of Mt. Epomeo. In the foreground you can see the Mt. Epomeo Green Tuff forming sub-vertical faces exposed along the fault zones. In the background lies the municipalities of Lacco Ameno (to the east) and Forio (to the west). The S. Montano beach is part of a little bay bounded by Mt. Vico and the Zaro lava plateau, is one of the best on the island and even has a wonderful spa. A climb of Mt. Epomeo is one of the most beautiful experiences for people visiting the island. The walk to the top can be difficult as it is rather steep in places and certainly not for the faint-hearted or unfit but is certainly suitable for people with average levels of fitness and lasts between an hour and an hour and a half depending on your fitness levels. Good walking clothing and footwear is essential. (photo www.visitischia.com)

The spectacular discordance of the volcanic succession along the Scarrupo di Panza cliff (Punta Imperatore in the southwestern part of the island). The lower section of the sequence is formed by the old lavas of Punta Imperatore (117 ka B.P.) and is overlain by a huge sequence of pyroclastic flow deposits (photo www.ischianews.com)

Very hot fumaroles along the western side of Maronti's beach (southern sector of the island). This is one of the hottest spot of Ischia, where tourists can eat the food cocked just with the natural heat of the ground (photo S.Carlino).

Appendix D

Ischia's Forgotten Observatory

The events surrounding scientific institutions, such as the birth of the Vesuvian Observatory, and, even earlier, that of the University of Naples Federico II, in some cases are not useful in encouraging political institutions to understand the importance of research centres in the cultural development and defence of a given area. This is certainly the case if we examine the events surrounding the creation, operation and closure of the Geodynamic Observatory of Casamicciola, on the island of Ischia. This new research and monitoring centre was set up in 1885 following the devastating earthquake that struck Casamicciola in 1883. At that time the Italian Parliament decided to set up this small observatory following requests from many parties and demands for greater security for the populations at risk.

The structure was directed by the Triestine Giulio Grablovitz (1846–1928), an enterprising self-taught man who was already part of the Royal Geodynamic Commission following the 1883 earthquake. The construction of the observatory took longer than expected, so that Grablovitz began the seismic observations by installing a temporary station at the Port of Ischia. The actual functioning of the geophysical observatory only began in 1898, when it was finally completed on the Grande Sentinella hill and lasted only until 1902, when the director once again transferred the equipment to the Port of Ischia. Grablovitz became interested in tidal phenomena, but mainly developed various instruments for recording earthquakes, both local and distant, which today would be called short and long period seismographs. Worthy of note is his apparatus for the recording of long period horizontal components, which he called a "seismic tank" (still visible today at the headquarters on Grande Sentinella). It consists of a circular vessel, filled with water, with a diameter of 1.5 m and a depth of 1 m. At the edges of the vessel there are two floats

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running N<->S and E<->W. The passage of long period seismic waves created movements in the water, which were magnified and recorded on a drum with smoked paper. To obtain a sufficiently reliable time reference, solar clocks were constructed. During the period of greatest activity, the Geological Observatory of Casamicciola managed two seismic stations, one at the Port of Ischia and the other on the Grande Sentinella, as well as a marine measurement station down at the Port. The instruments proved to function well, and recorded the 1905 Kangra earthquake in what today is Himachal Pradesh in India in and that in San Francisco in 1906 with the tide gauge at the Port recording the tsunami generated following the catastrophic Messina earthquake of 1908. Grablovitz, continued to perform seismic and meteorological surveys, but without implementing the island's monitoring network. In 1923 the Geodynamic Observatory of Casamicciola was abolished. Although it was a structure whose function and significance could have brought added value to the island of Ischia, bureaucracy and political obtuseness led to a failure to understand its real value. In the years following its closure, Grablovitz was authorised to use the observatory premises to continue certain observations, until shortly before his death in 1928. Part of the instrumentation still in use was transferred to the Trieste Observatory, while the headquarters of the Casamicciola Geodynamic Observatory was abandoned.

Discussion surrounding the island's Observatory began again in 1940, it being Prof. Placido Ruggiero, the chief engineer of the hydrographic service for the Civil Engineers for Campania, and Prof. Cristofaro Mennella who supported its restoration and expansion. The latter analysed the data collected by Grablovitz that had remained for years in the archives from which he obtained valuable data on the climatic characteristics of the island. The state-owned premises were reactivated and some of its instrumentation was restored. The two academics also promoted the creation of a committee, made up of representatives from scientific circles, to try to re-launch the monitoring structure. Prof. Mennella was determined to render the observatory a promoter and coordinator of geological and environmental studies for the development of the island. This was the beginning of a battle that was once again destined to fail.

The building that housed the Geodynamic Observatory is still there, near the Grande Sentinella, and amidst various vicissitudes and bureaucratic obstacles nothing has been done to restore dignity and functionality to the structure. What better place than Ischia, with its volcanic and tectonic phenomenologies, would there be to place a geodynamic observatory? What better context in which to help make this structure become an international study centre for students interested in volcanology? It was not to be thus and the old Geodynamic Observatory of Casamicciola still awaits an answer with regard to its fate.

Appendix E

The DInSAR Satellite Techinique: A Remote and Powerful Eye to Detect the Geological Phenomena

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The geological processes taking place several kilometers below the earth's surface, such as the seismogenic fault dislocations, magma accumulation, pressure variation in the magmatic reservoirs, etc, in many cases cause deformation of the earth's surface that can be measured with geodetic methods and remote sensing techniques, such as Differential SAR Interferometry (DInSAR). This is a well-established microwave remote sensing technique that, by exploiting two satellite images acquired at different times, allows estimating the surface deformations occurred between the two acquisitions with centimeter to millimeter accuracy. DInSAR systems are able to revisit the same area at regular intervals, providing information at very high spatial resolution of the observed scene. For instance, the ERS 1/2 and Envisat of ESA satellites, active since 1992 have a revisiting time of 35 days, while for the new generation sensors, such as the Italian constellation COSMO-SkyMed, the revisiting time was reduced to 8 days. These measures are shown by a series of colored bands, the so-called fringes or interferograms. The used electromagnetic waves are characterized by an alternation of crests spaced several cm. By "counting" these crests, the radar is able to understand how much is moved the object that is being observed. If the object is located hundreds of miles away, moving only a few centimeters, the number of crests

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that characterize the electromagnetic waves will change, allowing to detect and accurately measure the displacement with centimetric accuracy.

The interferometric techniques produce not only maps of ground deformation measured along the line of sight of the sensor; indeed, taking advantage of a series of images (instead of only two) acquired over time, it allow us to follow the temporal evolution of deformation. These information can be particularly valuable, for example, the measurement of ground deformation in volcanic areas is extremely important because these are often precursors of eruptions, or indicate an increase of volcanic activity. When we consider that the first satellites (ERS-1) used for this purpose have collected data from 1992, the deformation history of a volcano in the last 25 years can be analyzed with a previously unimaginable detail. Moreover, as a further advantage, compared to the more "traditional" techniques especially in case of eruption, these measurement are obtained without any necessity of access to the volcano.

Therefore, by using the DInSAR technique, it is possible to detect and monitor any kind of deformation on Earth surface, as the one induced by earthquakes, landslides and, for sure, volcanoes as in the case of the Campi Flegrei. As said, DInSAR benefits from the availability of long-time SAR archives because of the possibility to follow the evolution of the ground deformation. Figure A shows the mean deformation velocity map generated on large part of the Campania region by exploiting the ESA ERS and ENVISAT SAR measurements from 1992 to 2010. From this map, small displacements of Vesuvius volcano and Ischia are identified; while a more substantial deformation is observed in correspondence of the Campi Flegrei caldera both in terms of amplitude and temporal evolution of the displacement (see the displacement time series reported below). This kind of analysis clearly demonstrates the importance to dispose of long-term SAR archives for monitoring high risky areas. It is indeed worth noting that the current DInSAR scenario is characterized by the huge availability of SAR data acquired by several satellite constellations. Apart the already mentioned ERS 1/2 and ENVISAT SAR missions, during the last 20 years, many other SAR systems have been launched, as for instance the RADARSAT-1/2 Canadian missions, the ALOS-1/2 (JAXA) Japan satellites, the Italian COSMO-SkyMed (ASI) and the German TerraSAR-X (DLR) constellations, operating at different carrier frequencies and offering several spatial resolutions and ground coverage. More recently, starting from 2014 the new Copernicus Sentinel-1 satellites are supplying a massive SAR data flow due to their global coverage acquisition strategy. Sentinel-1 constellation consists of 2 satellites, which are fully operative and, on land, acquire every 6 days with the Interferometric Wide Swath mode, which guarantees a very large footprint of about 250 km and is specifically devoted to DInSAR applications. As an example of the Sentinel-1 potential, Fig. B shows the deformation in the 2014–2018 period measured at Campi Flegrei, which has experienced a resumption of the uplift.

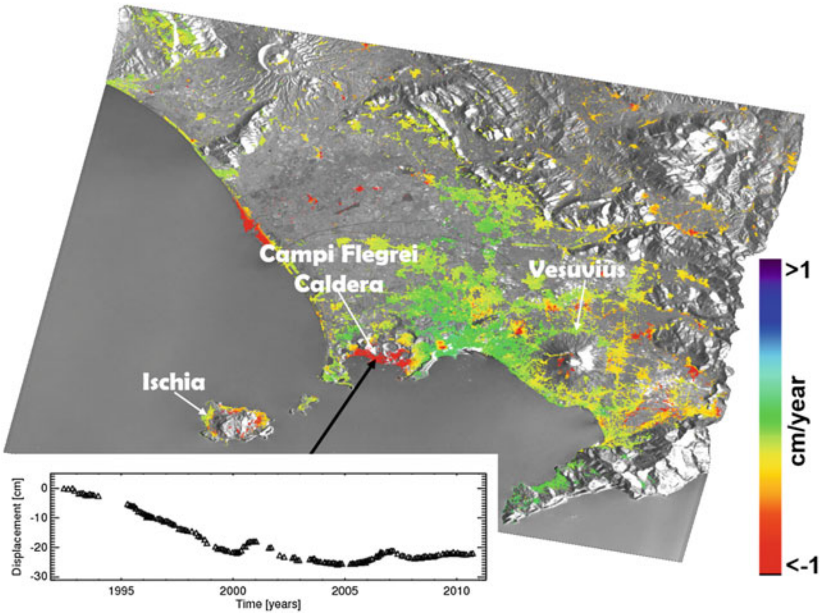


Fig. A Mean deformation velocity map in satellite Line of sight (LOS) obtained by exploiting ERS/ENVISAT SAR data collected from descending orbits on the Campania region from 1992 to 2010. The plot refers to the temporal evolution of the displacement of a point in the area of maximum deformation of the Campi Flegrei caldera

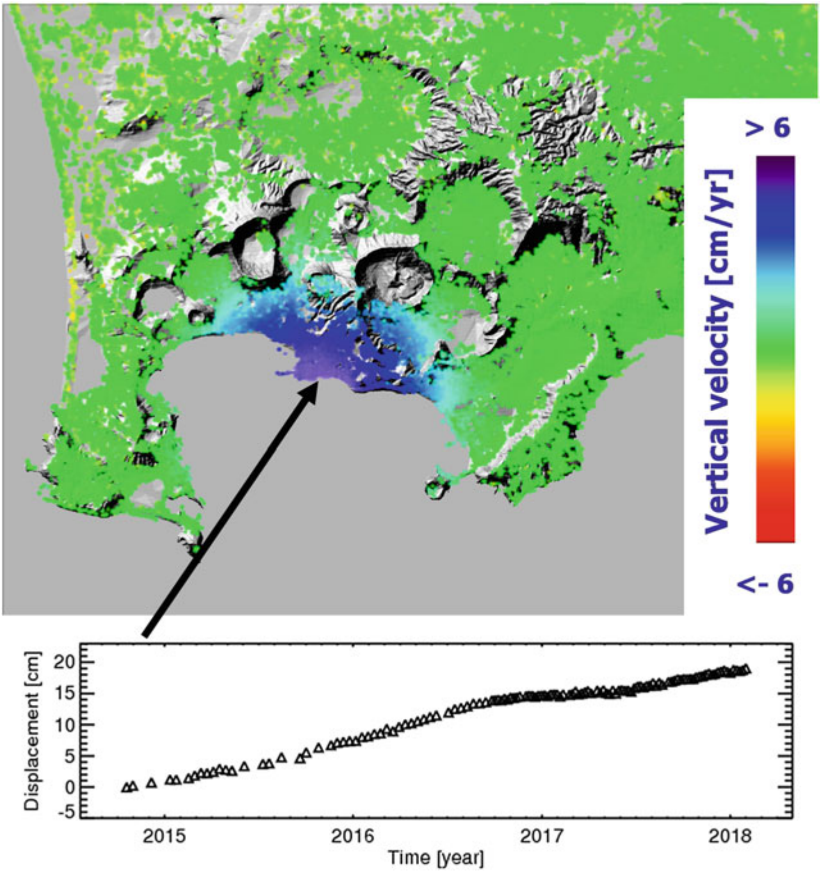
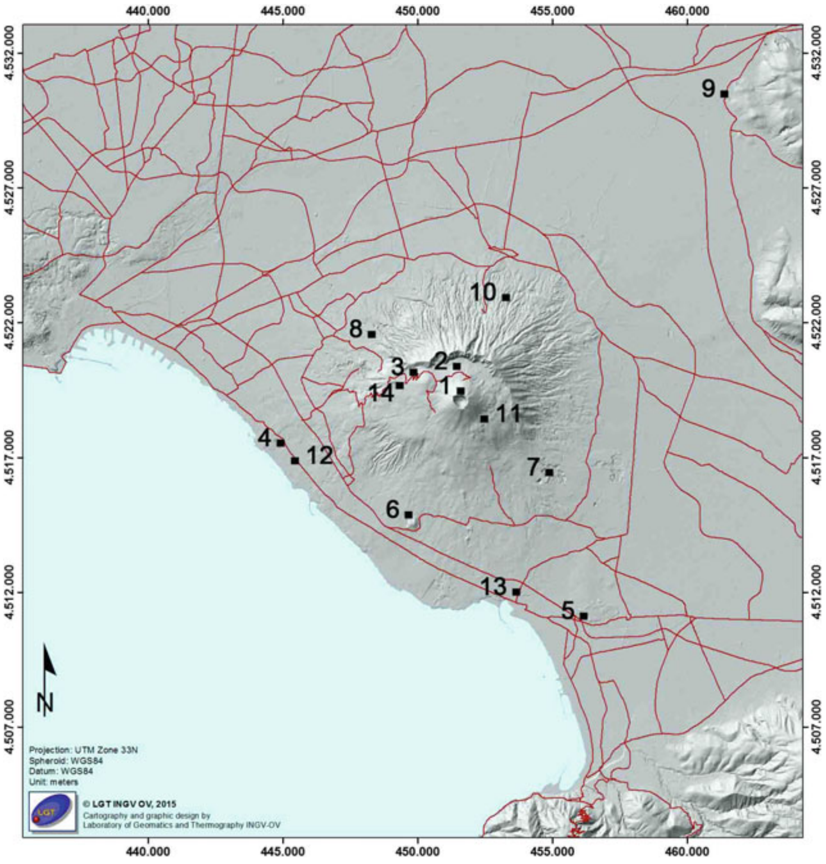


Fig. B Vertical deformation velocity map obtained by exploiting Sentinel-1 SAR data acquired from ascending and descending orbits on the Campi Flegrei from 2014 to 2018. The plot refers to the temporal evolution of the displacement of a point in the area of maximum deformation of the Campi Flegrei caldera

The Principal Sites to Visit Mentioned in the Text

Vesuvius and Its Surroundings



(**courtesy Eliana Bellucci Sessa, Geomatic Laboratory of OV-INGV**)

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1. The Crater (Gran Cono): a visit to the crater is fundamental for those wanting to observe the Neapolitan volcano and provides beautiful views of Naples, the Vesuvian villages and the Lattari Mountains. There are fumaroles inside the crater. You can arrive by car or bus from Ercolano or from Torre del Greco, reaching 1000 m and then continue on foot for climb of about 200 m along an easy path.
2. Valle dell'Inferno: this is certainly one of the most beautiful paths in the Vesuvius National Park. From here you can see numerous volcanic structures along the wall of the Somma caldera and some eruptive centres from the historical period. This is a site of volcanological and environmental interest.
3. Lava from 1944: this flow, produced during the last eruption of Vesuvius, is visible along some of the paths of the Vesuvius National Park, starting at low altitudes, from San Sebastiano to Vesuvius, or higher up from the Valle dell'Inferno. This is a site of volcanological and environmental interest.
4. Excavations of Herculaneum: where history and volcanology meet. This is one of the key stages for those visiting the Vesuvius area.
5. Pompeii excavations: one of the most visited archaeological sites in the world. It is necessary to dedicate an entire day for a thorough visit.
6. Camaldoli della Torre: a lateral crater formed in historical times on which stands the convent of the same name and from which you can admire a beautiful view towards the sea.

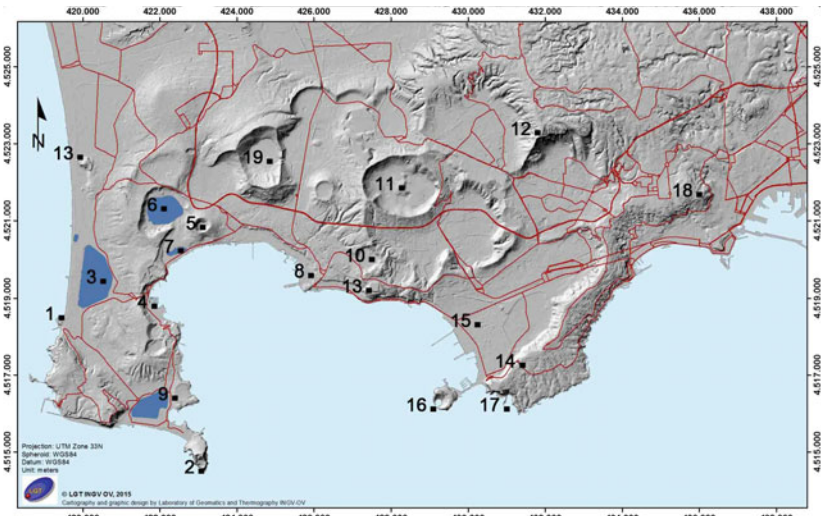
7–8. Cave di Terzigno e Pollena: for those concentrating on a more purely vulcanological and archaeological visit, the quarries of Vesuvius are extremely interesting sites. In the municipality of Terzigno, the Archaeological Park of the Cava Ranieri is certainly one of the places to visit. In the Municipality of Pollena Trocchia, however, the quarry of Carcavone is of great interest for vulcanologists for the sedimentation of volcanic products, deriving largely from the so-called "Pollena eruption" of 472 A.D.

9. San Paolo Belsito: for those wanting to take a look at life in Campania in the Early Bronze Age and the villages buried by the eruption of Vesuvius which occurred 3,800 years ago.
10. Lagno Macedonia: this is one of the many small valleys that cut into Monte Somma in the municipality of Somma Vesuviana, where you can see interesting layers of volcanic products from the ancient eruptions of Vesuvius. This is a site of volcanological interest.
11. Rope-like lava flows: along the path in the Vesuvius National Park that leads from Ottaviano to the Gran Cono, you can see some interesting lava

formations, created during both historical and recent activity of Vesuvius. This is an area of volcanological and landscape interest.

12. Villa Campolieto: one of the most beautiful villas of the Miglio D'Oro at Ercolano.
13. Villa di Poppea: grandiose in terms of size and for the quality of the frescoes, in the ancient Oplonti, today the town of Torre Annunziata. Archaeological excavations of Oplonti.
14. The Vesuvius Observatory: the oldest volcanological observatory in the world, now used as a museum. An obligatory stop during the ascent of Vesuvius.

Campi Flegrei and Surroundings



(**courtesy Eliana Bellucci Sessa, Geomatic Laboratory of OV-INGV**)

1. Torre Gaveta: a bay located in the western sector of the Campi Flegrei formed by a small sandy beach and tufaceous hillocks. At the bottom of the beach is the promontory of the same name where pyroclastic deposits can be seen from before and after the eruptions that generated the caldera.

2. Capo Miseno: this is the main seaside resort for Neapolitans. A beautiful beach, near Bacoli, which ends in the promontory of Capo Miseno which we can recognise as the remains of the ancient eruptive centre. An ideal place for long walks by the sea and to taste fish dishes in the many restaurants in the area. This is site of archaeological and volcanological interest.
3. Lake Fusaro: in the municipality of Bacoli, the lake was formed with the closure of the stretch of sea between the villages of Torregaveta and Cuma. In antiquity it was identified as the mythical *Acherusia palus*, the infernal marsh formed by the river Acheron. Here, by order of the Bourbon King of Naples Ferdinand IV, a hunting and fishing lodge was built, designed by Vanvitelli (the Casina Vanvitelliana).
4. Baia: the place of leisure. A charming maritime centre where you can visit the submerged Roman city, the castle of the same name, and taste excellent seafood. Not to be missed.
5. Monte Nuovo: this is the most recent volcano to erupt in the Campi Flegrei. It is a small cone of scoria formed during the eruption of 1538 and can be visited at the *Oasi Naturalistica di Monte Nuovo*, in front of Lake Lucrino.
6. Lake Averno: a lake of volcanic origin located in the western sector of the *l'Oasi Naturalistica di Monte Nuovo*. According to myth, this was an access to hell and for this reason the Roman underworld (Greek *Hades*) is also called *Avernos*. It is the ideal place to go for walks on its banks and buy different sorts of agricultural produce and food from local farmers. A site of volcanological interest.
7. Lake Lucrino: once home to the Roman military port (*Portus Julius*), it was connected to lake Averno that lies behind it by a navigable canal. Following the uplift of the caldera, the two lakes separated once again.
8. Rione Terra: this is the most ancient and fascinating place in Pozzuoli, located on a small promontory into the sea. According to the Greek historian Strabo, this small fortress was considered the landing-place of the ancient city of the Cumae and it was here therefore that, in all probability, in 529 B.C., the exiles from the island of Samos landed and founded Diceraachia, the government of the righteous. However, it was in Roman times that Pozzuoli and its fortress knew their period of greatest splendour. Absolutely unmissable.
9. *Piscina Mirabilis*: near the municipality of Bacoli, is a magical place not to be missed. On the promontory overlooking the port of Miseno, the *Piscina Mirabilis* is one of the largest preserved Roman cisterns (dating

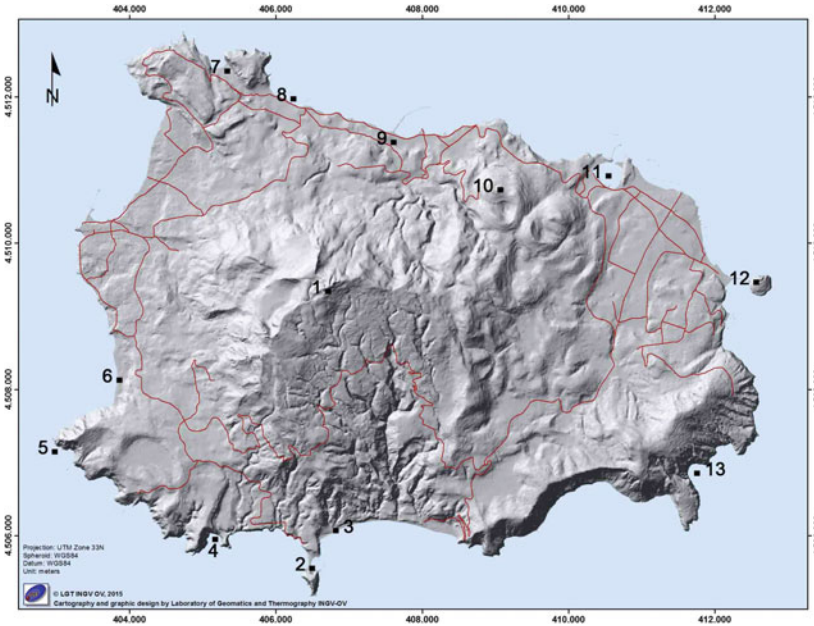
back to the time of Augustus). The terminus of the Serino aqueduct, it supplied the Roman fleet of the port of Miseno with water and has a capacity of 12,000 m^3.

10. Solfatara: located a little further east of Pozzuoli is a crater formed over 3000 years ago. It is one of the most visited sites in the Campi Flegrei, due to its impressive fumarolic manifestations that can be observed in the crater. Entry to the crater is subject to charges.
11. Astroni: this is among the largest craters in the Campi Flegrei area and certainly the best preserved in structure. It is crossed by natural paths and hides for birdwatchers, equipped with explanatory panels and interpretation boards, for a total of 15 km along a range of paths.
12. Camaldoli. the highest hill in the city of Naples, from which it is possible to obtain a beautiful view across most of the caldera of the Campi Flegrei and the islands in the Gulf of Naples. The hill, which borders the north-eastern edge of the caldera, is home to the Camaldoli Hermitage complex, founded in 1585 by Giovanni d'Avalos, the son of Alfonso of Aragon.
13. The La Starza marine terrace and Monte Olibano lava dome, located just east of the centre of Pozzuoli. La Starza is a marine terrace 40 m above sea level. The upper part of this terrace was once the coastline. The lifting has occurred in the last 10,000 years. The relief of Monte Olibano, near the Aeronautical Academy, consisting of a lava dome and is a site of volcanological interest.
14. Posillipo hill: this is one of the most evocative places in Naples. Geologically it is made up of the Neapolitan Yellow Tuff.
15. Bagnoli and the CFDDP: the former industrial site of Bagnoli, although not accessible to the public, can be seen from above, descending from Posillipo hill towards Nisida. This is a large area once occupied by the ILVA steel processing plant. The area has been the subject of a great deal of controversy due to the difficulty of its reconversion, ongoing for many years. Inside the former industrial site in 2012 a scientific drilling was performed, within the Campi Flegrei Deep Drilling Project (CFDDP) and which reached a depth of 500 m.
16. Nisida: this is an ancient volcanic edifice which forms an islet connected to the mainland by a small bridge. It is the location of the Naples juvenile prison and is clearly visible from the Posillipo hill.
17. Trentaremi: a beautiful bay located at the tip of Posillipo. The best way to visit it is to rent a canoe at one of the centres along the coast of Naples.

This is also the best way to observe the coast that is divided into numerous bays and small coves amidst the yellow tuff formations.

18. San Martino: one of the most evocative places in Naples from which to observe the panorama of the city with Vesuvius in the background. Do not miss the visit to the Certosa and Castel Sant'Elmo.
19. Gauro: a volcanic tuff crater, from whose southern edge you can see the beautiful panorama of the Phlegraean side of the islands of Ischia and Procida. The south-west side has collapsed, forming the Cirque of Teiano, while in the south-east side the gap of the "Porta del Campiglione" has been opened through which you access the crater of the same name which forms the base of Mount Gauro.

Ischia Island



(**courtesy Eliana Bellucci Sessa, Geomatic Laboratory of OV-INGV**)

1. Monte Epomeo: on a beautiful sunny day an ascent of Epomeo, even if tiring, rewards the climber with a unique and unforgettable sight. There are many possible routes to reach it. The itinerary from the south (Barano) will allow you to savour part of the geological, environmental and anthropological history of the island.
2. Sant'Angelo: an ancient eruptive centre, in the south of the island, where today there stands a marvellous fishing village. Very interesting from a vulcanological point of view, but also in scenic and culinary terms. Not to be missed.
3. Maronti: one of the most popular beaches, located in the south of the island, the most interesting elements are the numerous fumaroles around the westernmost part of the beach. Here it is possible to eat food cooked using the natural heat of the Earth. For those wanting to take a thermal bath, a stop is required at the ancient baths of Cavascura, which can be accessed along the beach.
4. Sorgeto: a splendid bay just west of Sant'Angelo. and a destination for tourists who want to take a swim in the sea even during the winter season, for the presence of hot springs along the rocky beach. It is also a site of archaeological and volcanological interest.
5. Punta Imperatore: this is the westernmost point of the island and the location of the lighthouse of the same name. It can be visited from the land, but from the sea it offers a spectacular view of volcanic succession along the overhanging cliffs.
6. Gardens of Poseidon: the largest baths on the island, near Forio. Not to be missed for those who love thermal baths.
7. San Montano: a magnificent bay located in the north-west of the island, in the municipality of Lacco Ameno, this is a beautiful beach set between two headlands and the setting for the magnificent thermal baths just behind. It is also a site of archaeological and volcanological interest.
8. The "Mushroom" of Lacco Ameno: this is a large block of green tuff that has slipped from Monte Epomeo, just in front of the small fishing town. The erosion of the sea has given this block a mushroom shape and it has become the symbol of Lacco Ameno. This is an ideal site for a walk by the sea.
9. Casamicciola: a beautiful town, located in the north, at the foot of Monte Epomeo, sadly famous for the devastating earthquake that razed it to the ground in 1883 at a cost of over 2,300 victims. It is a site of thermal and volcanological interest.

10. Monte Rotaro: From the square in front of the Casamicciola sports field, looking up the hill above, it is possible to make out the crater of the Rotaro eruption from which the lava flow of the same name was erupted. It is currently covered by a thick pine forest and is a site of volcanological and environmental interest.
11. Port of Ischia: an ancient port consisting of a crater of volcanic origin, opened up to the sea by works during the Bourbon era to allow the anchorage and landing of ships. It is the main port for the island, a place of commercial exchange and liveliness.
12. Castello Aragonese: lying in the east of the island, in the municipality of Ischia, this is a fortification that stands on an ancient trachytic lava dome, connected to the ancient village of Celsa by means of a 220 m long masonry bridge, known as Ischia Ponte and represents an ideal place for walks and to taste the local food.
13. San Pancrazio: in the south-east of the island, this stretch of coastline is formed by cliffs and natural river beds that outline the south side of the island, providing unique vistas. Best visited from the sea.