*Journal of Geography and Cartography (2021) Volume 4 Issue 2*
doi:10.24294//jgc.v4i2.443

## Original Research Article

# Geologic and geomorphologic study of the Terra Murata and Centane-Panoramica Sites (Island of Procida, Naples Bay, Southern Tyrrhenian Sea) aimed at solving some applied geological and geotechnical problems

**Gemma Aiello***

*Istituto di Scienze Marine (ISMAR), Consiglio Nazionale delle Ricerche (CNR), Sede di Napoli, Naples 80133, Italy. E-mail: gemma.aiello@iamc.cnr.it*

## ABSTRACT

A geologic and geomorphologic study aimed at solving some geological and geotechnical problems, regarding the massive seepage of meteoric waters in the coastal cliffs of the Island of Procida (Naples Bay, Southern Italy) composed of both tuffs and loose pyroclastic deposits, has been carried out in the geosites of Terra Murata (Middle Ages village and coastal cliff towards the Corricella Bay) and Centane-Panoramica (coastal cliff facing on the Tyrrhenian Sea).

A detailed geologic and geomorphologic survey has allowed to suggest solutions to the applied geological and geotechnical problems related to the occurrence of massive seepages of waters at the physical interface between pyroclastic rocks and loose pyroclastic deposits, characterized by different density, permeability and porosity and also controlled by a dense network of fractures, involving the pyroclastic deposits cropping out in the selected areas.

Field sampling and geotechnical laboratory analyses have been carried out to calculate the values of main geotechnical parameters of the yellow tuffs cropping out at the Terra Murata Promontory. At the same time, a detailed monitoring of the seepages of waters has been carried out through a detailed geological survey of the tuff outcrops of the promontory. The obtained results have suggested a strong control from both the geomorphologic instability of the coastal cliff and tectonic setting. At the Centane-Panoramica geosite, the geological survey, coupled with geotechnical analyses and standard penetrometric tests, has accordingly evidenced that the geomorphologic instability was mainly concentrated in the sectors of the tuff coastal cliffs facing seawards towards the Tyrrhenian Sea.

***Keywords:*** Geology; Geomorphology; Pyroclastic Rocks; Seepages of Water; Island of Procida; Naples Bay

**ARTICLE INFO**

Article history:
Received 10 July 2021
Accepted 30 August 2021
Available online 7 September 2021



## 1. Introduction

In this paper, a geomorphologic study of instability processes in two selected areas of the Island of Procida, located in the Naples Bay (Southern Tyrrhenian Sea), has been carried out. These areas are respectively located in the historical center of Procida (Middle Ages village of Terra Murata; **Figure 1**) and in correspondence of the coastal cliff joining the Pizzaco and Solchiaro promontories, herein named the Centane-Panoramica geosite.

One aim of this paper is to outline the geologic framework of the two study areas, which are characterized by a different geologic setting. In the Terra Murata quarter, abundant seepages of waters have been detected both in the highest zone of the Middle Ages village (place after the walls) and on the coastal cliff facing the Corricella Bay (Salita Castello; **Figure 2**). They involve the volcanic successions and are located, in particular, between the volcanic tuffs and the loose pyroclastic deposits, widely outcropping at the Terra Murata promontory. Since the seepages involve several edifices, it is necessary to address a geomorphological and geotechnical study aimed at individuating their control factors in order to purpose technical solutions to these geological problems.

In this paper, a geologic framework of the Terra Murata quarter will be delineated, referring to the stratigraphic relationships between the volcaniclastic rocks and deposits and to the hydrogeologic factors, which have probably controlled the seepages of waters. Some possible technical solutions will be individuated to study and solve this problem, which was probably also controlled by the occurrence in the subsurface of ancient Borbonic sewers/old tanks/cavities.

Terra Murata represents the historical center of the Island of Procida and is an ancient Middle Age village located on a tuff coastal cliff high 90 m a.s.l. Terra Murata can be accessed only through a steep street, traveling along which the village of Marina Corricella may be seen. There are some ancient doors to access the Middle Age village of Terra Murata ("Porta di Ferro" & "Porta di Mezz'Omo"), representing old points of admittance. The important structures of the village are represented by the S. Michele Arcangelo Abbey, the old village of Terra Murata, the viewpoint of Borgo street, the Place of the Arms, the Prison Complex, the old doors, the viewpoint of the Two Guns and the S. Margherita Convent (**Figure 3**).

**Figure 1**. View of the Middle Ages village of Terra Murata (Island of Procida), overlying a tuff coastal cliff facing on the Tyrrhenian Sea (Naples Bay).

**Figure 2.** The tuff coastal cliff of Terra Murata towards the Corricella Bay (Island of Procida, Naples Bay).


**Figure 3.** Sketch representation of the structures of the Middle Age village of Terra Murata.

The Centane-Panoramica geosite, characterized by the coastal street joining the promontories of Pizzaco and Solchiaro, where the Solchiaro yellow tuffs widely outcrop, offers many examples of geomorphologic instability. They have been observed in outcrops of the coastal cliffs facing seawards towards the Tyrrhenian Sea. These sectors have been used as the dumps of undifferentiated deposits. The present-day flat morphology of some areas may deceive on their condition of stability, which may result in precarious conditions, if these areas should be submitted to loads not proportional to the geotechnical parameters of stability of the undifferentiated Quaternary deposits or in conditions of water flooding, also considering the lacking of a drainage system of meteoric waters.

The coastal cliffs of the Island of Procida are incised in yellow tuffs and/or pyroclastic deposits and include the Terra Murata coastal cliff, facing towards the Corricella Bay and the coastal cliff of the Centane-Panoramica geosite. These cliffs show a geomorphologic instability consisting of erosional lineaments and landslides, which were controlled by different factors. These factors include the marine erosion at the toe-of-slope, the wind action on the sub-vertical walls of cliffs and the instability of the superficial strata cropping out at the top of the coastal cliffs, composed of loose pyroclastic deposits alternating with paleosoils. Other factors are represented by the occurrence of undrained absorption waters and by the uncontrolled flow of superficial waters.

A sketch geologic map of the Island of Procida has been constructed (**Figure 4**), showing the occurrence of volcanic deposits having a different lithology and age. They can be placed in the general geologic setting of the formation of the whole Neapolitan and Phlegrean areas. The formation of the Vivara, Terra Murata and Punta Serra volcanoes has been ascribed to an age older than 75 ky B.P. through radiometric absolute dating[1]. The emplacement of the Campanian Ignimbrite and its proximal facies ("Breccia Museo") has been dated back to 37 ky B.P.

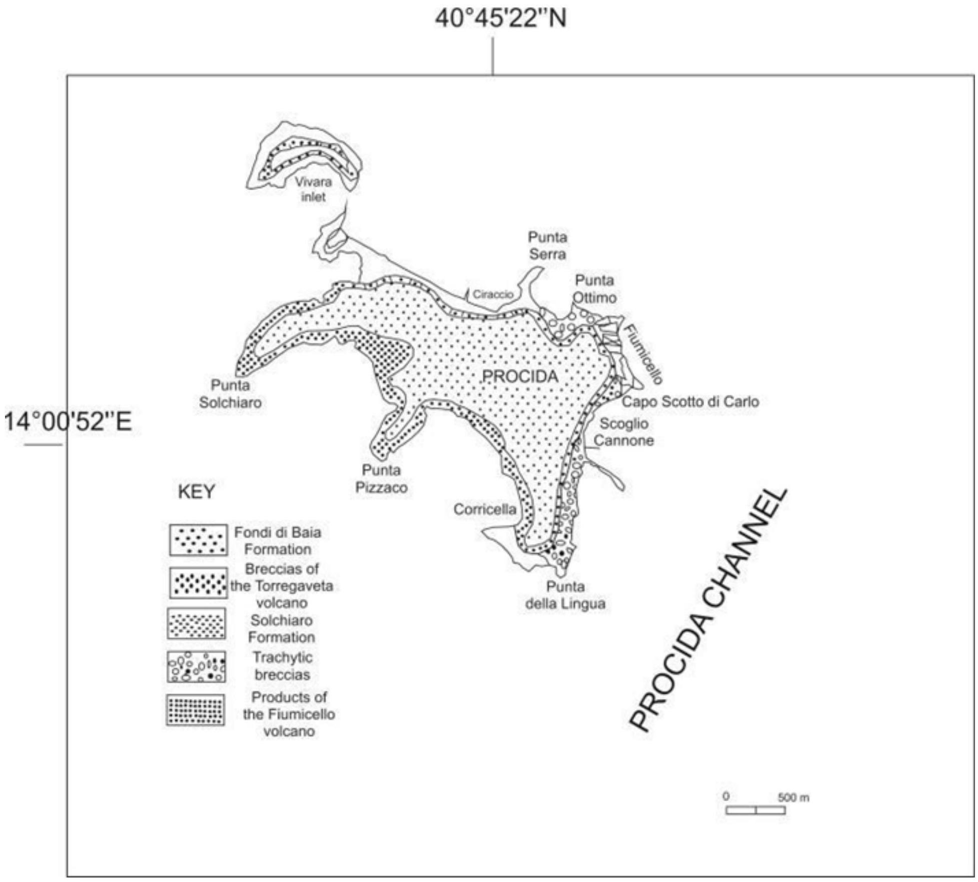

**Figure 4.** Sketch geological map of the Island of Procida (Naples Bay).

During the time interval ranging between 30 and 10 ky B.P., a volcanic activity having a great intensity and area diffusion has led to the formation of the Solchiaro Volcano (average age 22 ky B.P.) and the emplacement of the stratified white tuffs cropping out at Soccavo and in the Naples town. During this period, other main events are represented by the formation of the Torregaveta Volcano and the emplacement of the Neapolitan Yellow Tuff about 15 ky ago[2].

During the time interval younger than 10 ky B.P., the formation of lava domes, scoria cones and monogenetic pyroclastic volcanoes took place (e.g. Monte Nuovo, Astroni, Agnano, Capo Miseno, Bacoli, Montagna Spaccata, Monte Ruscello)[3-7].

## 2. Materials and methods

The key methods of this paper are represented by the geological and geomorphological survey carried out on volcanic rocks and deposits. The volcanic rocks of Campania have been deeply studied by different authors through different methodologies, including volcanology, geochemistry, age dating and applied geological aspects[2,3,8-16]. Relevant geological surveys in volcanic deposits have been recently carried out also in the Etna Volcano, Sicily. For example, Branca *et al.* and Groppelli & Goette have addressed to the construction of significant geological maps of volcanic areas[17,18].

The geotechnical analysis of collected samples have also been performed in order to calculate such significant geotechnical parameters as the angle of inner friction (FI), the wet weight-volume ratio (GA), the dynamic resistance at the point (Rd), the un-drained cohesion (Cu) and the compression strength (σ).

The technical characteristics of the undifferentiated deposits located at the top of coastal cliffs have been determined on disturbed samples collected during standard penetrometric tests (SPT). As explained in the results, some samples of undifferentiated deposits have been collected during the SPT tests (wells 1, 2 and 5). Some geotechnical analyses have been performed in order to calculate the general technical characteristics of the deposits, while sedimentological analyses have been performed to evaluate their grain-size.

The standard penetrometric tests (SPT) have allowed for the thickness calculation of the undifferentiated deposits overlying the rocky substratum in the coastal cliffs and for the determination of the physical-chemical characteristics of the crossed grounds. The calculation has been based on algorithms correlating the significant geotechnical parameters with the number of blows of the standard penetrometer (Nspt).

## 3. Results

### 3.1 Stratigraphy of the Procida volcanic deposits

Several volcanic units having a different nature and age, crop out in the Procida Island. The lithology and the stratigraphy of these deposits are herein described. They come from localized monogenetic volcanic edifices, also if intercalations of volcanic materials having a Phlegrean and Ischian provenance are present. The age of the volcanic centers is reported from Fedele *et al.*[1]

#### 3.1.1 Vivara volcano (age about 75 ky)

The Vivara Volcano includes the Vivara Inlet and the S. Margherita Promontory. It is represented by a well-stratified ring of yellow and grey tuffs, having a circular shape (**Figure 5**). The lower part of the Vivara tuffs is formed by massive metric banks of yellow tuffs, constituted by a yellow cineritic matrix, completely lithified and by shardy dark grey lapilli having a trachybasaltic composition. They grade upwards to grey stratified tuffs, slightly lithified. The transition among the two units crops out at Punta Capitello and in the coastal cliff between Punta Mezzogiorno and Punta Alaca, while the culmination of the crateric rim may be seen northwards of Punta Mezzogiorno and S. Margherita vecchia.

**Figure 5.** The Vivara volcano**.**

#### 3.1.2 Pozzo Vecchio Volcano (age about 75 ky)

It is characterized by a succession starting with hydromagmatic yellow tuffs forming a ring-shaped volcano, whose crateric rim is well visible in the bay between Punta Serra and Punta Ottimo (**Figure 6**).

**Figure 6**. The tuff coastal cliff between the Corricella Bay and the Pozzo Vecchio beach (“Spiaggia del Postino”)**.**

The edifice of the Pozzo Vecchio Volcano is composed of thinly stratified tuffs, grading upwards into fall deposits having a coarser grain-size, poorly sorted, with intercalations of thin cineritic levels. A scoria cone, formed by banks having a reddish colour, is superimposed on the northern flank of the volcanic edifice. The scoria deposits are overlain by a lava flow having an alkali-trachytic composition.

### 3.1.3 Terra Murata Volcano (age about 75 ky)

It is formed by stratified yellow tuffs. The lower part of the volcanic edifice is composed of zeolitized yellow tuff, thinly stratified and well lithified. In the upper part of the sequence, a transition to less lithified tuffs including pumice levels may be observed. The Terra Murata tuffs are covered by levels of Plinian pumices, which cannot be reached in outcrop and by the distal deposits of the Fiumicello Volcano. On the eastern coastal cliff of Terra Murata, the superimposition and the thinning upwards of the Fiumicello grey tuffs on the Terra Murata yellow tuffs may be observed.

### 3.1.4 Fiumicello Volcano (age ranging between 75-60 ky)

It is composed of lithified hydromagmatic deposits of an eruptive center located in the northern sector of the Island of Procida. The distal deposits of this eruptive center show a wide area dispersal, being used as a marker horizon in the stratigraphic correlations between Procida and Monte di Procida[9]. The Fiumicello tuffs crop out along the coastal cliff between Punta del Pioppeto and Capo Bove, while the distal facies crop out at Punta della Lingua.

At Punta del Pioppeto and Punta della Lingua, the deposits of the Fiumicello unit are unconformably overlain by the Campanian Ignimbrite. In the proximal sections the deposits are composed of yellow and grey tuffs, having a trachybasaltic composition, hialoclastitic and thinly stratified. Scattered dome-shaped structures and impact prints in correspondence with lava blocks and yellow tuffs occur. The deposits of the distal facies are characterized by alternating grey ashes, ashes with lapilli and banks of scoria and lapilli derived from pyroclastic fall-out.

### 3.1.5 Campanian Ignimbrite (age 37 ky)

The Island of Procida represents an area where several volcanic units genetically related to the Campanian Ignimbrite crop out. They are interlayered between sequences of massive ashes, separating them from the Solchiaro tuffs at the top and from the Epomeo Green Tuffs at the base. These units are (from the base to the top):

(1) Pyroclastic ash flows

Massive cineritic banks rich in pumices showing at their base a characteristic level formed by pumices. Couple of levels of welded grey and pink ashes.

Levels having a decimeter thickness up to one meter (Scotto di Carlo outcrop) and corresponding to the distal facies of the Campanian Ignimbrite.

(2) Piperno bank

It is formed by scorias and lavas, rich in matrix, grading upwards into the Breccia Museo. A cineritic facies occurs at their base, eroding the underlying deposits and cropping out at Punta della Lingua, Scotto di Carlo and Cimitero.

(3) Breccia Museo

It is represented by the proximal facies of the Campanian Ignimbrite, showing a pumice pyroclastic flow at their top.

(4) Pumice flow

Level of gray and green pumices rich in degassing structures. In the section of Spiaggia del Postino, it is characterized by a layer rich in blocks.

### 3.1.6 Solchiaro volcano (age 22 ky)

The deposits forming this unit are genetically related to the eruptive activity of the Solchiaro tuff ring, representing the youngest eruptive activity of the Island of Procida. The crateric rim has been identified in the south-eastern sector of the Island of Procida, between the Pizzaco promontory (**Figure 7**) and the Solchiaro promontory (**Figure 8**). The deposits of the Solchiaro volcano widely occur in the upper part of the stratigraphic sequences cropping out in many coastal cliffs of the Island of Procida. They crop out also at Vivara, to the north of Punta Mezzogiorno and around Punta Capitello. Next to the volcanic vent, outcropping along the coastal street bounding the Pizzaco and the Solchiaro promontories (Panoramica Street), a transition from stratified yellow tuffs to stratified grey tuffs has been observed, suggesting a deposition in a mostly subaerial environment.

**Figure 7.** The Pizzaco promontory (Island of Procida, Naples Bay)**.**

**Figure 8.** The Solchiaro Promontory (Island of Procida, Naples Bay)**.**

## 3.2 The Terra Murata coastal cliff towards the Corricella Bay

### 3.2.1 State of the geosite

One of the selected geosites is located in the north-western sector of the Island of Procida. In fact, the S. Michele church and the "Conservatorio delle Orfane" palace are located next to a sub-vertical slope, separating the Terra Murata village from the sea.

The subsurface lithostratigraphic reconstruction has been simplified from the occurrence of this slope. In fact, the slope allows for the direct observation of the rocky strata underlying the church for an overall thickness of 90 meters. The subsurface is constituted by a stratified tuffaceous formation, probably latitic in nature. This formation shows two different facies, having distinct lithotechnical characteristics (**Figures 9, 10, 11** and **12**).

**Figure 9.** The Terra Murata coastal cliff towards the Corricella Bay, where the superimposition of two facies with different lithotechnical characteristics may be seen**.**

**Figure 10.** Detail of the Terra Murata coastal cliff, showing the stratigraphy of the pyroclastic successions having different technical characteristics**.**

**Figure 11.** Detail of the Terra Murata coastal cliff whose outcrop shows the stratigraphy of the pyroclastic successions and a deep cave incised in tuffs**.**

**Figure 12.** The upper part of the Terra Murata coastal cliff, showing the superimposition of the grey facies (to the top) on the yellow facies (to the base).

The first facies, yellow in colour, is completely lithified. The second facies, grey in colour, is semi-coherent. The two facies are not separated by an abrupt lithostratigraphic boundary. In fact, the lithified yellow facies grades upwards or laterally to the semi-coherent grey facies. This is probably due to the mechanisms controlling the individuation of the two facies, such as the processes of post-depositional zeolitization, realized after an incipient hydrothermal activity and involving the most part of the tuffaceous products of the Island of Procida.

The hydrothermal activity, realized from the base to the top of the succession and proceeding along radial directions has provoked the neoformation of zeolitic minerals in the basal and central parts of the formation, which has consequently reached a lithoid consistency, assuming a yellow colour. The gradual decreasing of the hydrothermal action in the peripheral areas of the formation has determined the differentiation of a residual facies, having a grey colour and a semi-coherent consistency (**Figure 9** and **10**). Moreover, the dipping of the strata has clearly indicated that the emission centre of the tuff pyroclastic products was located next to the coast, in front of the S. Michele church.

From a mineralogic and petrographic point of view, the Terra Murata tuffs are formed by abundant glassy pumices and shales, together with trachytic inclusions and by sanidine and biotite crystals, coupled with minerals of neoformation pertaining to the group of zeolites (e.g. cabasite and phillipsite)[1].

The coastal cliffs of the Island of Procida show in outcrop the lithostratigraphic and geometric relationships between the described formations. Proceeding from the Terra Murata promontory towards north, a gradual thickness increase of the grey facies with respect to the yellow one may be observed. Below the S. Michele church, the semi-coherent grey facies is lacking, while it reaches a thickness of about 30 m some tens of meters to the north.

Above the described tuffs heterogeneous breccias crop out ("Breccia di Punta della Lingua"). Above these breccias, genetically related to the Campanian Ignimbrite, the volcanic succession is composed of one or more paleosols, overlain by pyroclastites genetically related to the Solchiaro volcano and by pumice products genetically related to the Phlegrean Fields ("Fondi di Baia Formation")[19].

The geomorphology of the Terra Murata coastal cliff is herein discussed. The cliff is high about 92 m a.s.l., representing the highest part of the Island of Procida. The outcrops surrounding the S. Michele Abbey and the "Conservatorio delle Orfane" palace have not been strongly involved by erosional processes, while the coastal cliff between the promontories of Punta dei Monaci and Punta della Lingua has undergone a strong erosional action due to the sea. The coastal cliff retreated in consequence of erosional processes. The waves, bumping with the base of slope, have provoked its erosional retreatment through a physical and chemical action with the formation of deep furrows. Deep fractures have been observed downthrowing the coastal cliff at several places, which have isolated some packages, making unstable the slope. Moreover, the action of the atmospheric agents, particularly of the rain, tends to deepen the fractures, progressively widening them and triggering the occurrence of rock falls.

**Table 1.** Geotechnical parameters of yellow tuffs at the Terra Murata coastal cliff (Island of Procida)

| | |
|---|---|
| **Volume weight** | 1.3-1.5 g/cm$^3$ |
| **Load of compression rupture** | 30-70 kg/cm$^2$ |
| **Angle of inner friction (FI)** | 15°-20° |
| **Cohesion** | 20-30 kg/cm$^2$ |

The volcanic deposits cropping out along the Terra Murata coastal cliff have shown technical characteristics similar to those ones of the Neapolitan Yellow Tuff (NYT) deposits[20]. Some samples have been collected to perform the geotechnical analyses, allowing for the calculation of the geotechnical parameters resumed in **Table 1**.

### 3.2.2 Seepages of waters and their possible nature

At the Terra Murata geosite, the monitoring of the seepage of waters has been carried out through a detailed geologic and geomorphologic survey coupled with technical consideration. In particular, a first survey has been carried out in the place located after the door marking the beginning of the Middle Ages village. This survey has been carried out aimed at reconstructing the relationships between the seepages of water documented in this area by one hundred year (next to the door) and the similar phenomena of seepages of water documented below the street, namely Salita Castello.

At the Terra Murata place, dry and wet tuffs crop out to a few distance. Here the seepages of waters are very consistent. A first outcrop is characterized by grey tuffs, very lithified, including a coarse-grained fraction, composed of scoriaceous lapilli and dark pumice levels. At lower heights, other wet outcrops have been observed, characterized by grey-yellow tuffs, similar to those ones observed in the first outcrop. Proceeding towards lower heights, another outcrop has been surveyed, composed of dry tuffs.

The occurrence of both cavities in the subsurface (ancient pools) and the system of the old sewer, Borbonic in age, serving again some houses, should be pointed out. Recently, after the cleaning of the old sewer, the seepage of waters tended to decrease. The tuff outcrops located in the place, now appearing dry, underlie the houses linked to the modern sewer. Accordingly to the testimonies of the indoor people, some houses located in the upper part of the Terra Murata historical village are not linked to the modern sewer. In these cases, the waters should be drained towards the valley, finding preferential pathways in the joints layering and following the gradient of the tuff formations.

A second survey has been carried out on the tuff coastal cliff below the Salita Castello Street (Terra Murata) in a private house located on the coastal cliff facing towards the Marina Corricella. Here the seepages of waters are very abundant, forcing the house's inhabitants to carry out works of ordinary maintenance. After the partial consolidation of a sector of the coastal cliff, located laterally to the house, realized through cement injections and the waterproofing of fractures, the seepage of waters were reduced. After a short time, the seepages abundantly re-started, producing a water sheet continuously falling, such as a small cascade.

The obtained results have evidenced some elements of interest. The first element is represented by the high geomorphologic instability of the Terra Murata coastal cliff towards the Marina Corricella. The coastal cliff has been arranged through some holding walls. One of them is disposed longitudinally to the houses, while other ones are disposed in a punctual way. Other interventions consist of metallic wire nettings put on single parts of the coastal cliff and of cement injections. The high geomorphologic instability has been favored by selective erosion of grey tuffs, representing the upper terms of the stratigraphic succession forming the coastal cliff. This erosion was probably controlled by the stratification of the tuffs, which are composed of lithified levels (holding out) and semi-coherent levels (coming back).

The second element is represented by the occurrence of fractures and small vertical faults, allowing for a block down throwing of the tuffs. Together with the joint layering, showing a general seaward immersion, they represent preferential drainage pathways for the inshore waters. The permeability of the upper grey tuffs should be primary, due to the scarce lithification of the deposits, rich of inter-granular spaces and secondary, due to the strong fracturing, favoring the water circulation.

## 3.3 The Centane-Panoramica geosite (coastal cliffs between the Pizzaco and Solchiaro Promontories)

### 3.3.1 State of the geosite

The area bounded by the Pizzaco and Solchiaro coastal cliffs is constituted by a degrading tuff cliff, on which deposits coming from authorized excavations have been spilled. The incongruence and the quantity of the deposits have make necessary interventions finalized to the re-development of the area, depending on the performed geologic analysis, aimed at determining the subsurface lithology and the height trending of the area.

The geologic analysis, properly integrated by geological and technical tests for the determination of the stratigraphy and of the technical characteristics of the tuffs, representing the acoustic substratum and of the overlying undifferentiated deposits, has been carried out on the seawards sectors of the coastal cliffs. The A area was analyzed, used as a dump up to recent times.

The coastal cliff morphology has been strongly modified since they have been used as dumps of recent undifferentiated deposits. They constitute a wedge having a kilometric extension, overlying the yellow tuffs of the Solchiaro Formation along the coastal cliff between the Pizzaco and Solchiaro Promontories.

The technical characteristics of these deposits have been determined on disturbed samples, previously collected during standard penetrometric tests (SPT) through geotechnical and grain-size analysis. The results obtained from the SPT tests have allowed calculating the thickness of the undifferentiated deposits, overlying the rocky substratum of the Solchiaro tuffs and the physical and chemical characteristics of the crossed grounds. They have been calculated through algorithms of correlation, relating the geotechnical parameters with the number of blows (Nspt). The calculated geotechnical parameters are listed in **Table 2** (Solchiaro tuffs).

**Table 2.** Geotechnical parameters of Solchiaro yellow tuffs at the Pizzaco coastal cliff (Island of Procida) calculated through the correlation of Standard Penetrometric Tests (SPT)

| | |
|---|---|
| **Angle of inner friction (FI)** | 37°-40° |
| **Wet weight-volume ratio (GA)** | 1.65 t/m$^3$ |
| **Dynamic strength at the point (Rd)** | 50.94 kg/cm$^2$ |
| **Un-drained cohesion (Cu)** | 0 |
| **Compression strength (σ)** | 1.5-2 kg/cm$^2$ |

The SPT tests have evidenced the following technical and mechanical characteristics of the undifferentiated deposits along the coastal area, namely the A area, located in the Centane-Panoramica geosite. The drill site S1 is reported as an example.

#### 3.3.1.1 Geotechnical parameters at the drill site S1

The SPT tests have been carried out at a depth of 3.6 m, occurring at the top of the rocky substratum composed by tuffs. Between the field plan and the depth of 3.6 m, alternating strata of grounds having a variable consistency, ranging between very dense and loose, have been found.

The general characteristics have been determined in laboratory on a disturbed sample drilled at a depth of 3.4 m from the field plan during the SPT test at the drill site S1 (**Table 3**). The grain-size analysis has shown slightly muddy gravelly sand.

**Table 3.** General characteristics of the undifferentiated deposits at the drill site S1

| | |
|---|---|
| **Specific weight of the granules** | 2.36 g/cm$^3$ |
| **Volume weight** | 1.50 g/cm$^3$ |
| **Water content** | 35.70 % |
| **Void ratio** | 1.67 |
| **Porosity** | 62.53 % |
| **Saturation degree** | 100% |

The state of the geosite is relatively different in the areas located onshore of the coastal street (B and D areas) with respects to the areas located seawards of the coastal street (A area). While the first ones are characterized by outcropping lithoid pyroclastic rocks (Solchiaro yellow tuff) along steep coastal cliffs, the second ones show undifferentiated deposits on flat morphological surfaces, overlying at depth the rocky substratum composed of tuffs.

### 3.3.2 Geomorphologic instability

The high geomorphologic instability of the coastal cliff surrounding the Chiaia beach (Island of Procida) has been recently evidenced from frequent landslides coupled with strong erosion. The accommodation of the coastal cliff has been recently carried out in the frame of the FESR project through the emplacement of containing walls, adopted in order to contain the erosional phenomena and to make sure the public baths.

The two areas located inwards of the De Gasperi Street (Centane-Panoramica geosite), namely the D and B areas, now used as recreation places for children do not have a significant geomorphologic instability if compared with the areas of the coastal cliff located seawards, also due to their lithology, mainly tuffaceous.

The Solchiaro tuffs crop out along a sub-vertical rocky slope in the first area, located landwards and form a slope having a low gradient in the second area, located towards the valley. At a first analysis, these areas may be considered as more stable with respect to the areas located seawards, being characterized by outcropping lithoid grounds.

It must be singled out the occurrence of small fractures, involving the tuff coastal cliff. At the present-day state of geosites, these fractures do not cause problems of stability. In the future, they need to be monitored and controlled in order to forecast, with the onset of the erosion, the rock falls of the blocks isolated from these fractures.

Moreover, it is worth noting the occurrence of undifferentiated deposits at the base of the tuff coastal cliff, which should be removed to realize the environmental re-development of the area[21].

## 4. Discussion

Selected areas of the Island of Procida, whose geologic history is strictly related with the eruptive centers of the Phlegrean Fields and the Island of Ischia, have been studied. Procida and Vivara are two volcanic islands, located in an intermediate position between the active calderas of the Phlegrean Fields and the Island of Ischia. A deep knowledge on the stratigraphy and the volcanological evolution of the Phlegrean Fields and of Ischia has been produced by volcanological studies[3,14,22,23].

The stratigraphy and volcanology of Procida and Vivara have been deeply studied by many scholars[1,8,24-28]. The volcanic deposits cropping out in the Island of Procida have been generally explained as the result of eruptions coming from local eruptive centers. Moreover, these studies have indicated the occurrence of several pyroclastic units, linked to the eruptive activity of the Ischian and Phlegrean volcanic complexes, inter-layered in the volcanic successions erupted from the local volcanic centers of Procida and Vivara.

In the pyroclastic sequences of the two islands, the occurrence of several regional markers and their stratigraphic correlation[1,25] allows for the volcanological reconstruction and the stratigraphic framework of the volcanic products of Ischia and Procida islands in the frame of the volcanic successions of Ischia and Phlegrean Fields.

The Phlegrean Fields, with the Ischia and Procida islands, represent a complex volcanic system formed by a set of small monogenetic volcanoes, disposed along a E-W trend and fed by a potassic magmatism. Recent studies on the area including the Phlegrean Fields and the Procida and Vivara islands have evidenced the existing correlation between the phases of volcanic activity for the comprehension of the volcanic processes older than the eruption of the Neapolitan Yellow Tuff[3,14,29].

The volcanic breccias cropping out at Marina di Vita Fumo (Monte di Procida) and the Procida island (Punta della Lingua, Scotto di Carlo and Pozzo Vecchio) are genetically related to a main phase of volcanic activity, whose eruptive center was probably located in the Procida Channel. Other six eruptive centers have been recognized in the Procida and Vivara islands, including the Vivara volcano, the Fiumicello volcano, the Terra Murata volcano, the Punta Serra volcano and the Solchiaro volcano. Moreover, the study of the marine area between Procida and Ischia has revealed two distinct volcanic morphologies, namely “La Catena” and “Le Formiche di Vivara”, having a basaltic chemistry, similar to that one of the Procida volcanic products[8,30-32].

The volcanological evolution of the Island of Procida and Vivara is herein outlined based on the geological data. According to the stratigraphic reconstructions of Rosi *et al.*[11] and Fedele *et al.*[1], Procida and Vivara have been formed by the accumulation of volcanic products of pyroclastic fall and pyroclastic flux, coming from the surrounding volcanic complexes of Ischia and Phlegrean Fields.

The oldest volcanic deposits detected in outcrop are represented by the products of the volcanic centers, respectively trachybasaltic and trachytic, of Vivara, Pozzo Vecchio and Terra Murata. In all the three vents, eruptive centers formed by stratified yellow tuffs occur. In the Pozzo Vecchio Volcano, the growth of the tuff cone has been followed by a scoria eruption and by the final emission of a lava flow, having a trachytic composition. The depositional environment was probably submarine for the base of the volcanic edifices and subaerial for the middle and upper part of the tuff cones.

The eruptive scenario was represented by an explosive activity in a shallow water environment (yellow tuffs of Vivara, Terra Murata and Pozzo Vecchio), followed by a progressive isolation of the eruptive conduits from the sea with the eruption of wet hydromagmatic products, represented by the grey and white tuffs forming the upper parts of the Vivara and Terra Murata tuffaceous successions and by volcanic products, which do not show any evidence of magma-water interaction (Pozzo Vecchio scorias followed by the final lavas). All the three edifices have allowed for the construction of an emerged volcanic field.

Starting from this period, the deposition of products erupted from the surrounding areas started. Among them, the first ones are represented by the deposits linked to the explosive activity in a subaerial environment, happened in the Ischia Channel in correspondence to the "Formiche di Vivara" saddle (Procida Channel). Coarse-grained breccias and pyroclastic surge deposits erupted from the center overlie part of Vivara and the north-western sectors of Procida. No available radiometric data exist on these deposits.

During the next period, ranging between 74 and 55 My, Vivara and the emerged centers of Pozzo Vecchio and Terra Murata have been overlain by neritic banks of Plinian pumices, coming from the Ischia Island. In this period, the volcanic activity newly starts with the trachybasaltic eruptive center of Fiumicello, whose hydromagmatic deposits are interlayered between the B and C Plinian pumices of the Pignatiello Formation.

The Fiumicello eruption has deeply modified the morphology of the north-eastern sector of the Island of Procida, with a thick deposit of stratified yellow tuffs and thinly stratified grey tuffs, overlying the eruptive centre of Pozzo Vecchio, from Punta di Pioppeto to Punta Ottimo and the northern sector of the Terra Murata eruptive cone.

Plinian fall deposits of the Island of Ischia are overlain by the trachybasaltic products of a second hydromagmatic eruption, coming from the Ischia Channel ("Canale d'Ischia superiore")[11]. It is represented by breccias levels, fall lapilli and pyroclastic surges, cropping out in the Vivara inlet and the sector from Ciraccio and Pozzo Vecchio.

The second trachybasaltic eruption of the Ischia Channel is followed by the eruption of the Epomeo Green Tuffs of the Island of Ischia (55 ky)[23,33-39] and of the Campanian Ignimbrite of the Phlegrean Fields (37 ky)[12,40-47].

A main modification of the morphology of the Island of Procida realized after the eruption of the Epomeo Green Tuffs of Ischia due to the infilling of the lows located between previous eruptive vents. Another phase of infilling happened after the eruption of the volcanic products related to the Campanian Ignimbrite, 37 ky ago. The present-day flat morphology of the Island of Procida has been controlled by these volcanic events.

A next morphological change happened about 19 ky ago after the eruption of the Solchiaro yellow tuffs, representing the last local event tested based on volcanic stratigraphy. The Solchiaro volcano is a cone of stratified yellow tuffs linked to a hydromagmatic explosive activity in a shallow water environment. The corresponding pyroclastic surge deposits overlie the most part of the Island of Procida and subordinately, Vivara and S. Margherita. After the products of the Solchiaro volcano, there is the deposition of distal fall ashes (loose pyroclastites) produced by the Phlegrean eruptions ("Fondi di Baia Formation"[19] or "Unità dei Tefra superiori"[11]). These deposits widely crop out in the upper terms of the Procida and Vivara successions, having an average thickness of 3-4 m. They have been deposited during the old post-caldera activity of the Phlegrean Fields (Phase A of Rosi and Sbrana[3]) and during prehistorical eruptions (Bronze Age) of the Ischia Island.

The tracts of high-relief coasts of the Island of Procida represent erosional surfaces, developed during the geological time as a consequence of the interactions between volcanism, tectonics, eustasy and climate. Perhaps, they represent transitional landforms controlled by geomorphological and geomechanical processes coupled with the anthropic activity. Therefore, they represent landforms varying during the geological time and unstable, also if the velocity of variations of the landforms may be variable.

One of the most relevant phenomena controlling the variation in shape of the high-relief coasts is represented by the coastal landslides, whose peculiarity is due to be controlled by the sea actions, if compared with the continental landslides[48-59].

The tracts of the high-relief coasts of the Island of Procida show a notable articulation due to the complex volcano-tectonic and geomorphologic evolution of the island, during which several landslides realized[60]. They are mainly represented by rock falls and topples (WP/WPLI, 1994), whose triggering has been controlled by lithostratigraphic and structural setting. In fact, the alternating lithoid and loose levels have caused a differential erosion of the coastal cliff, with the formation of brackets, respectively holding out and coming back, having an unstable equilibrium and triggering landslides.

The tectonic setting of the coastal cliffs of the Island of Procida is characterized by fractures, both vertical and parallel to the slopes. At several places, the coastal cliffs show a more articulated profile, consisting of a sub-vertical basal slope, on which another slope develops, ranging in gradient from 35° to 45° in loose pyroclastites (Fiumicello, Solchiaro Promontory, and Vivara Inlet) and joining with an upper flat surface. In these cases, apart from rock falls involving the tuff deposits of the basal slope, slides and flows involving the loose pyroclastites of the upper slope have been observed.

In this study, both in the Terra Murata coastal cliff facing the Marina Corricella towards the Tyrrhenian sea and the Pizzaco and Solchiaro coastal cliffs (Centane-Panoramica geosite) have been analyzed. Geological survey coupled with SPT, geotechnical and grain-size analyses has revealed a high geomorphologic instability of these coastal cliffs. This instability is accompanied, in the Terra Murata coastal cliff, by important seepages of water at the contact between the tuffaceous formations, characterized by different permeability and lithology.

## 5. Conclusion

The tracts of high-relief coasts of the Island of Procida show a strong articulation and complexity due to the volcano-tectonic and geomorphologic evolution of the island. This geological and geotechnical study has evidenced that the seepages of waters mainly occur in the tuff outcrops located in the place signing the admittance to the Terra Murata Middle Ages village and on the slopes below the "Salita Castello" street, pertaining to the tuff coastal cliff facing towards the Corricella Bay (Tyrrhenian Sea).

The coastal cliffs are distinguished from seawards dipping rocky walls, whose evolution is mainly controlled by the erosional action of the sea at the foot of slope through the undermining of the cliff foot and by the consequent phenomena of deformation, fracturing, rupture and mass gravitational movements, with individuation of coastal landslides[57,58].

The geologic and geomorphologic study of some tuff outcrops located in the Middle Ages village of Terra Murata, representing the historical centre of the Island of Procida, has evidenced the occurrence of main water seepages, located in correspondence with pyroclastic formations having different technical characteristics and also controlled by a dense network of fractures. In some way, these water seepages have also been controlled by the occurrence of the ancient Borbonic siewer, with tanks or cavities now occurring in the subsurface. They are particularly abundant in the tuff outcrops located in the place apart from the door marking the entrance to the Middle Ages village of Terra Murata and below the Salita Castello street. The involved lithologies are represented by lithified grey tuffs, including an abundant coarse-grained fraction, composed of scoriaceous lapilli and dark pumices and subordinately, by grey-yellow tuffs.

The geologic and geomorphologic study of the Centane-Panoramica geosite has been involved in a project of environmental redevelopment and has been carried out through SPT tests and geotechnical analyses. Detailed results have been reported by Aiello[21].

The obtained results have evidenced a higher security of the areas located landwards of the coastal street joining the Pizzaco and the Solchiaro promontories (D and B areas), not showing a high geomorphologic instability and being characterized by outcrops of lithoid and coherent deposits (Solchiaro tuffs). On the contrary, the seawards areas (A and C areas), located towards valley from the street and at the top of the coastal cliff show a higher geomorphologic instability, mainly relatively to the upper part of the slope, quite unstable, since these areas have been used as dumps up to recent times.

Some detailed conclusions are herein reported, relatively to the single areas.

B area: this area, previously used as a recreation park for children, is generally adapted to its use. The flat surface, located at the top of the coastal cliff, laterally joins a rocky sub-vertical slope incised in the Solchiaro tuffs. These grounds, being lithoid and coherent, do not show problems of geomorphologic instability. The geologic setting of this area should be controlled relatively to the future state of the geosites. In fact, the occurrence of longitudinal fractures having a random distribution implies the isolation of hazardous rocky pieces and their rock fall due to increasing erosion.

D area: this area, previously used as a recreation park for children, is generally adapted to its use. Next to this area the Solchiaro tuffs crop out along a slope having a low gradient, showing a general immersion of the strata towards the street.

A area: the flat morphology of the seawards slopes on the coastal street joining the Pizzaco and the Solchiaro coastal cliffs may be misleading on their stability conditions, which may result in precarious conditions. This may happen if these areas should be undertaken to loads not proportional to geotechnical parameters of stability of the undifferentiated deposits or during channel filling.

The geomorphologic instability of the undifferentiated deposits overlying the Solchiaro tuffs is quite high on the coastal slopes facing towards the Tyrrhenian Sea, since they are represented by loose pyroclastic deposits with scarce technical characteristics. Moreover, the slopes are unstable since these deposits have been reworked up to recent times.

The SPT tests have been finalized to the calculation of density and inner angle of friction (FI), which is related to the shear strength and the depth of the underlying rocky substratum. FI has allowed evaluating the maximum loads and considering the interventions of redevelopment and consolidation, if necessary in these areas.

The SPT tests have been performed in a highly unstable area (A area), long about 100 m and located to 46 m a.s.l. Its lithostratigraphic setting is characterized by undifferentiated loose deposits overlying the yellow tuffs, which are potentially prone to slide. The tests have been carried out in drill sites located on the seawards rim of the A area next to the break in slope marking the coastal cliff top.

Some geotechnical analyses have been carried out on samples collected during the SPT tests to calculate the general technical characteristics of the undifferentiated deposits (**Table 3**). The obtained results have indicated the occurrence of a wedge of undifferentiated deposits ranging in thickness from 6.5 to 7 m and composed of slightly muddy gravelly sands with low water content.

**Table 3.** General characteristics of the undifferentiated deposits at the drill site S1

| | |
|---|---|
| **Specific weight of the granules** | 2.36 g/cm$^3$ |
| **Volume weight** | 1.50 g/cm3 |
| **Water content** | 35.70 % |
| **Void ratio** | 1.67 |
| **Porosity** | 62.53 % |
| **Saturation degree** | 100% |

## Ethics statement

The author states that this manuscript abides by the ethical norm required.

## Conflict of interest

No conflict of interest was reported by the author.

## References


1. Fedele L, Morra V, Perrotta A, *et al.* Carta Geologica Regionale alla scala 1:10.000. Isole di Procida e Vivara (con note illustrative). Regione Campania, Settore Difesa del Suolo, Geotermia e Geotecnica, Napoli, Italy; 2012.
2. Deino AL, Orsi G, De Vita S, *et al.* The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera — Italy) assessed by 40Ar/39Ar dating method. Journal of Volcanology and Geothermal Research 2004; 133(1-4): 157–170.
3. Rosi M, Sbrana A. The Phlegrean Fields. Quaderni De La Ricerca Scientifica; 1987. p. 175.
4. De Vita S, Orsi G, Civetta L, *et al.* The Agnano–Monte Spina eruption (4100 years BP) in the restless Campi Flegrei caldera (Italy). Journal of Volcanology and Geothermal Research 1999; 91(2-4): 269–301.
5. Arienzo I, Moretti R, Civetta L, *et al.* The feeding system of Agnano–Monte Spina eruption (Campi

Flegrei, Italy): Dragging the past into present activity and future scenarios. Chemical Geology 2010; 270(1-4): 135–147.

6. Bevilacqua A. Doubly stochastic models for volcanic hazard assessment at Campi Flegrei Caldera. Springer Verlag; 2016. p. 250.
7. Iovine RS, Fedele L, Mazzeo FC, *et al.* Timescales of magmatic processes prior to the ~4.7 ka Agnano-Monte Spina eruption (Campi Flegrei caldera, Southern Italy) based on diffusion chronometry from sanidine phenocrysts. Bulletin of Volcanology 2017; 79(2): 18. doi: 10.1007/s00445-017-1101-4.
8. Di Girolamo P, Stanzione D. Lineamenti geologici e petrologici dell'Isola di Procida. Rendiconti Società Italiana Mineralogia e Petrologia 1973; 24(5): 81–126.
9. Pescatore TS, Rolandi G. Osservazioni preliminari sulla stratigrafia dei depositi vulcanoclastici nel settore SW dei Campi Flegrei. Italian Journal of Geosciences 1981; 100(2): 233–254.
10. Di Girolamo P, Ghiara MR, Lirer L, *et al.* Vulcanologia e petrologia dei Campi Flegrei. Bollettino della Società Geologica Italiana 1984; 103: 349–370.
11. Rosi M, Sbrana A, Vezzoli L. Stratigrafia delle isole di Procida e di Vivara. Bollettino GNV 1988; 4: 500–525.
12. De Vivo B, Rolandi G, Gans P, *et al.* New constraints on the pyroclastic eruptive history of the Campanian Volcanic Plain (Italy). Mineralogy and Petrology 2001; 73: 47–65. doi: https://doi.org/10.10 07/s007100170010.
13. Rolandi G, Bellucci F, Heizler MT. *et al.* Tectonic controls on the genesis of ignimbrites from the Campanian Volcanic Zone, southern Italy. Mineralogy and Petrology 2003; 79: 3–31. doi: https://doi.org/10.10 07/s00710-003-0014-4
14. De Astis G, Pappalardo L, Piochi M. Procida volcanic history: New insights in the evolution of the Phlegrean volcanic district (Campania Region, Italy). Bulletin of Volcanology 2004; 66: 622–641. doi: https://doi.org/10.1007/s00445-004-0345-y.
15. Revellino P, Hungr O, Guadagno FM, *et al.* Velocity and run-out simulation of destructive debris flows and debris avalanches in pyroclastic deposits, Campania region, Italy. Environmental Geology 2004; 45: 295–311. doi: https://doi.org/10.1007/s002 54-003-0 885-z.
16. De Vita P, Napolitano E, Godt JW, *et al.* Deterministic estimation of hydrological thresholds for shallow landslide initiation and slope stability models: Case study from the Somma-Vesuvius area of southern Italy. Landslides 2013; 10: 713–728. doi: https://doi.or g/10.1007/s10346-012-0348-2.
17. Branca S, Coltelli M, Groppelli G. Geological Evolution of Etna Volcano. In: Bonaccorso A, Calvari S, Coltelli M (editors). Geophysical Monograph Series. Blackwell Publishing Ltd; 2004. p. 49–63. doi: 10.1 029/143GM04.
18. Groppelli G, Goette LV. Stratigraphy and geology of volcanic areas. Geological Society of America; 2010. ISBN: 9780813724645.
19. Rittmann A. Origine e differenziazione del magma ischitano. Sch-weizerische Mineralogische und Petrographische Mitteilungen 1948; 28: 643–698.
20. Scarpati C, Cole P, Perrotta A. The Neapolitan Yellow Tuff — A large volume multiphase eruption from Campi Flegrei, Southern Italy. Bulletin of Volcanology 1993; 55: 343–356.
21. Aiello G. Studio geologico del comprensorio Centane-Panoramica (Isola di Procida. Golfo di Napoli). Consiglio Nazionale delle Ricerche (CNR), Monografia, Rapporto Tecnico, edito da CNR Solar (Biblioteca Centrale del Consiglio Nazionale delle Ricerche "G. Marconi"), luglio 2016.
22. Di Girolamo P, Rolandi G. Vulcanismo sottomarino latite-basaltico-latitico (serie potassica) nel canale di Ischia (Campania). Rendiconti Acc. Sc. Fis. e Mat. in Napoli 1975; 42: 561–596.
23. Vezzoli L. Island of Ischia. Roma: Quaderni De La Ricerca Scientifica; 1988. p. 230.
24. Parascandola A. I crateri dell'Isola di Procida. Bollettino Società Naturalisti in Napoli 1924; 40: 57–60.
25. Perrotta A, Scarpati C, Luongo G, *et al.* Stratigraphy and volcanological evolution of Campi Flegrei and Procida Island. In: Stratigraphy and Geology of Volcanic Areas. GSA Special Papers 2010; 464: 185–189.
26. Putignano ML, Cinque A, Lozej A, *et al.* Late Holocene ground movements in the Phlegrean Volcanic District (Southern Italy): New geoarcheological evidence from the islands of Vivara and Procida. Mediterranée 2009; 112: 43–50.
27. Putignano ML, Schiattarella M. Geomorfologia strutturale e domini di frattura dei fondali marini pericostieri dell'Isola di Procida (Campi Flegrei insulari, Italia meridionale). Italian Journal of Quaternary Sciences 2010; 23(2): 229–242.
28. Aiello G, Marsella E. Interactions between Late Quaternary volcanic and sedimentary processes in the Naples Bay, Southern Tyrrhenian Sea. Italian Journal of Geosciences 2015; 134(2): 367–382. doi: 10.3301/IJG.2014.56.
29. Aiello G, Insinga D, Iorio M, *et al.* On the occurrence of the Neapolitan Yellow Tuff tephra in the Northern Phlegraean offshore (Eastern Tyrrhenian margin, Italy). Italian Journal of Geosciences 2017; 136: 263–274.
30. De Alteriis G, Donadio C, Ferranti L. Morfologia e strutture di apparati vulcanici sommersi nel Canale d'Ischia (Mar Tirreno). Memorie Descrittive della Carta Geologica d'Italia 1994; 52: 85–96.
31. Aiello G. New insights on the Late Quaternary geologic evolution of the Ischia Island coastal belt based on high-resolution seismic profiles. Italian Journal of Geosciences 2018; 137(1): 87–106. doi: 10.3301/I JG.2017.19.
32. Aiello G, Marsella E, Passaro S. Stratigraphic and structural setting of the Ischia volcanic complex (Naples Bay, Southern Italy) revealed by submarine seismic reflection data. Rendiconti Lincei 2012; 23: 387–408.

33. Gillot PY, Chiesa S, Pasquarè G, *et al.* <33,000-yr K–Ar dating of the volcano–tectonic horst of the Isle of Ischia, Gulf of Naples. Nature 1982; 229: 242–245. doi: https://doi.org/10.1038/299242a0.
34. Orsi G, Gallo G, Zanchi A. Simple-shearing block resurgence in caldera depressions: A model from Pantelleria and Ischia. Journal of Volcanology and Geothermal Research 1991; 47(1-2): 1–11.
35. Mele R, Del Prete S. Fenomeni di instabilità dei versanti in Tufo Verde del Monte Epomeo (isola d'Ischia – Campania). Bollettino della Società Geologica Italiana 1998; 117(1): 93–112.
36. Tibaldi A. Vezzoli L. Late Quaternary monoclinalic folding induced by caldera resurgence at Ischia, Italy. Geological Society of London, Special Publications 2000; 169: 103–113.
37. De Vita S, Di Vito MA, Gialanella C, *et al.* The impact of the Ischia Porto Tephra eruption on the Greek colony of Pithekoussai. Quaternary International 2013; 305: 142–152. doi: https://doi.org/10.1016/j.quaint.2013.01.002.
38. Brown RJ, Orsi G, De Vita S. New insights into Late Pleistocene explosive volcanic activity and caldera formation on Ischia (Southern Italy). Bulletin of Volcanology 2008; 70: 583–603. doi: https://doi.org/10.1007/s00445-007-0155-0.
39. Della Seta M, Marotta E, Orsi G, *et al.* Slope instability induced in volcano-tectonics a san additional source of hazard in active volcanic areas: the case of Ischia Island (Italy). Bulletin of Volcanology 2012; 74(1): 79–106.
40. Barberi F, Innocenti F, Lirer L, *et al.* The Campanian Ignimbrite: A major prehistoric eruption in the Neapolitan area (Italy). Bulletin of Volcanology 1978; 41(1): 10–31.
41. Fisher RV, Orsi G, Ort M, *et al.* Mobility of large-volume pyroclastic flow — Emplacement of the Campanian Ignimbrite, Italy. Journal of Volcanology and Geothermal Research 1993; 56(3): 205–220.
42. Civetta L, Orsi G, Pappalardo L, *et al.* Geochemical zoning, mingling, eruptive dynamics and depositional processes — The Campanian Ignimbrite, Campi Flegrei Caldera, Italy. Journal of Volcanology and Geothermal Research 1997; 75(3-4): 183–219.
43. Pappalardo L, Civetta L, D'Antonio M, *et al.* Chemical and Sr-isotopical evolution of the Phlegraean magmatic system before the Campanian Ignimbrite and the Neapolitan Yellow Tuff eruptions. Journal of Volcanology and Geothermal Research 1999; 91(2-4): 141–166.
44. Giaccio B, Isaia R, Fedele FG, *et al.* The Campanian Ignimbrite and Codola tephra layers: Two temporal/stratigraphic markers for the Early Upper Palaeolithic in southern Italy and Eastern Europe. Journal of Volcanology and Geothermal Research 2006; 177(1): 208–226.
45. Pyle DM, Ricketts GD, Margari V, *et al.* Wide dispersal and deposition of distal tephra during the Pleistocene 'Campanian Ignimbrite/Y5' eruption, Italy. Quaternary Science Reviews 2006; 25(21-22): 2713–2728.
46. Costa A, Folch A, Macedonio G, *et al.* Quantifying volcanic ash dispersal and impact of the Campanian Ignimbrite super-eruption. Geophysical Research Letters 2012; 39(10): L10301. doi: 10.1029/2012GL051605.
47. Fitzsimmons KE, Hambach U, Veres D, *et al.* The Campanian Ignimbrite Eruption: New Data on Volcanic Ash Dispersal and Its Potential Impact on Human Evolution. PLoS One 2013; 8(6): e65839. doi: https://doi.org/10.1371/journal.pone.0065839.
48. Edil TB, Le Vallejo LE. Mechanics of coastal landslides and the influence of slope parameters. Engineering Geology 1980; 16(1-2): 83–96.
49. Clark AR, Moore R, Palmer JS. Slope monitoring and the early warning systems: application to coastal landslides on the south and east coast of England, UK. Trondheim: Proceedings of the International Symposium on Landslides; 1996. p. 1531–1539.
50. Cruden DM, Varnes DJ. Landslide types and processes. In: Turner AK, Schuster RL (editors). Landslides: Investigation and mitigation (Special Report). Washington DC, USA, National Research Council, Transportation and Research Board Special Report 1996; 247: 36–75.
51. Montgomery W. Groundwater hydraulics and slope stability analysis: Elements for prediction of shoreline recession (PhD thesis). Western Michigan University; 1998. Available from: https://scholarworks.wmich.edu/dissertations/1583/.
52. Hall J, Lee EM, Meadowcroft IC. Risk-based benefit assessment of coastal cliff protection. Proceeding of the Institution of Civil Engineers-Water and Maritime Engineering 2000; 142(3): 127–139.
53. Iadanza C, Trigila A, Vittori E, *et al.* Landslides in coastal areas of Italy. Geological Society of London Special Publications 2009; 322(1): 121–141.
54. Abellan A, Calvet J, Vilaplana JM, *et al.* Detection and spatial prediction of rock falls by means of terrestrial laser scanner monitoring. Geomorphology 2010; 119(3-4): 162–171.
55. Bozzano F, Mazzanti P, Prestininzi A, *et al.* Research and development of advanced technologies for landslide hazard analysis in Italy. Landslides 2010; 7(3): 381–385.
56. Thiebes B. Theoretical Background. In: Landslide Analysis and Early Warning Systems. Springer Theses (Recognizing Outstanding Ph.D. Research). Berlin, Heidelberg: Springer. 2012.
57. Matano F, Iuliano S, Somma R, *et al.* Geostructure of Coroglio tuff cliff, Naples (Italy) derived from terrestrial laser scanner data. Journal of Maps 2016; 12(3): 407–421.
58. Esposito G, Salvini R, Matano F, *et al.* Multitemporal monitoring of a coastal landslide through SfM-derived point cloud comparison. Photogrammetric Record 2017; 32(160): 459–479.
59. Leshchinsky B, Olsen MJ, Mohney C, *et al.* Mitigating coastal landslide damage. Science 2017; 357: 981–982.
60. Calcaterra D, Del Prete S, Mele R. L'influenza dei fenomeni franosi sugli insediamenti costieri del dis-

tretto flegreo (Campania, Italia). Proc. Internat. Conf. CITTAM2003. The requalification of Mediterranean coasts among tradition, development and sustainability, Naples, June 26-28, 2003. Arte Tipografica Editore, 524–534, Napoli, Italy.