Late Holocene landscape evolution of the Gulf of Naples (Italy) inferred from geoarchaeological data

Pietro P.C. Aucelli, Aldo Cinque, Gaia Mattei, and Gerardo Pappone

ABSTRACT

The mapping of landforms in the Gulf of Naples is fundamental to understanding the recent evolution of this perithyrrenian basin controlled by several systems of Quaternary faults and characterised by the presence of the Campi Flegrei and Somma Vesuvius volcanoes. In this paper a 1:85,000 map of the recent evolution of the Gulf of Naples coasts is presented. This cartographic product has been obtained using a compilation of previously published geoarchaeological coastal studies integrated with new field data. The morphogenetic map suggests a differential evolution of various coastal stretches over the past 2000 years driven not only by measured vertical ground movements and eustatic sea-level rise (of 1 m) but also by eruptions of Mt. Vesuvius, in particular the Plinian eruption of 79 AD and the subsequent reworking of its products, as well as by the erosive action of the sea.

1. Introduction

Geoarchaeology aims to understand the human-environment relationship within an evolving environment (Bravi, Fuscaldo, Guarino, & Schiattarella, 2003), in order to reconstruct – in a specific area and period – the connection between the history of human settlement and culture and environmental changes (Barker & Bintcliff, 1999).

Coastal geoarchaeology, in particular, can use archaeological remains as constraints on the age of ancient shorelines and on the position of ancient sea levels (Morhange & Marriner, 2015; Vacchi et al., 2016); conversely, geological evidence provides paleogeographic and paleoenvironmental guidance useful to archaeological interpretations (Anzidei et al., 2011; Auriemma & Solinas, 2009). Along Mediterranean shores, numerous evidence near the coasts, such as production structures, town structures, landing places, and ports are recognisable and sometimes well-preserved. Some artefacts that are today submerged can provide important information to reconstruct the ancient coastal landscape (Antonioli et al., 2007; Caputo & Pieri, 1976; Fleming, 1969; Furlani et al., 2013; Lambeck, Anzidei, Antonioli, Benini, & Esposito, 2004; Marriner, Morhange, & Doumet-Serhal, 2006; Morhange & Pirazzoli, 2005; Pirazzoli, 1987; Rovere, Stocchi, & Vacchi, 2016; Scicchitano, Antonioli, Berlinghieri, Dutton, & Monaco, 2008).

Coastlines and geomorphological features such as cliffs, shorelines and sandbars, lagoons, estuaries, etc. are known to be among the most dynamic elements of the physical landscape. Such dynamics are directly related to the coastal processes that belong to endogenic factors (tectonics, isostasy, and volcanism) and surface processes (erosion, transport and sedimentation). Over the short term, seasonal and catastrophic meteoric events and human impacts can directly interfere with coastal changes. Over the long term, however, climate changes are the main factor influencing coastal evolution due to relative sea-level rises (Anzidei et al., 2014; Aucelli et al., 2016c; Brancaccio et al., 1991; Di Paola, Aucelli, Benassai, & Rodríguez, 2014; Lambeck et al., 2011; Pappone, Alberico, Amato, Aucelli, & Di Paola, 2011; Pappone et al., 2012; Shennan, Long, & Horton, 2015) along with volcanism, tectonic and volcanotectonic movements (Antonioli & Silenzi, 2007; Morhange, Marriner, Laborel, Todesco, & Oberlin, 2006; Santangelo et al., 2017).

Finally, in recent centuries, human impact on coasts and river basins have caused modifications of the sensitive Mediterranean coastal environment (Amato et al., 2012, 2013). The interaction of coastal processes and human impacts determines the overall evolutionary trend of coastlines (Alberico et al., 2012).

The Gulf of Naples is an example of the continued interaction between humans and volcanoes, as this area was densely inhabited since Greek times. As
described by Strabo, the beauty of the Gulf led the construction of many villas and gardens along the whole coastal area during the Greek–Roman age. The archaeological remains of these structures are now submerged or buried by the volcanic products of Vesuvius and have inspired this research, aimed at reconstructing the Roman landscape and studying the phenomena that have influenced it’s evolution.

The purpose is to present a map representing the coastal change that has occurred since Roman times along the coasts of the Gulf of Naples, by means of geomorphological and geophysical surveys carried out at several submerged geochronological sites of Roman time, taking into account the coastline position during the Last Glacial Maximum (LGM) and during the last interglacial period (MIS 5).

2. Geological and geomorphological setting

The Gulf of Naples is a NE-trending set of faults globally shaping a half graben characterised by thick volcanic units erupted from the Campi Flegrei and Vesuvius volcanoes (Aucelli, Brancaccio, & Cinque, in press, Figure 1; Milia, Torrente, Russo, & Zuppetta, 2003). The structure of the Gulf of Naples is controlled by numerous Quaternary fault systems, NE–SW trending SE-dipping and NW–SE trending SW dipping, linked to the last stages of the opening of the Tyrrhenian Sea (Fedele et al., 2015; Milia, 2010). Between the Middle and Upper Pleistocene, the fault systems were responsible for the development of the half-graben of the Gulf of Naples and Sorrento Peninsula fault block ridge (Milia & Torrente, 2003).

This extensional basin covers about 1000 km² and has the typical physiographic features of a passive continental margin, with its continental shelf slope (between –140 and –180 m of depth) and basin (Aiello et al., 2001; Milia & Torrente, 1999).

The Gulf of Naples, characterised by both monogenetic volcanoes and other volcanic and pyroclastic rocks, is bordered to the south by the carbonate succession of the Sorrento Peninsula, to the north by the Campi Flegrei volcanic area and to the east by the

![Figure 1. Geological sketchmap of Gulf of Naples.](image)
Vesuvian coast (Figure 1; Bonardi, d’Argenio, & Perrone, 1988; Fedele et al., 2015; Iannace et al., 2015; Santacroce & Sbrana, 2003).

The Campi Flegrei volcanic district includes Procida island and several submarine vents and monogenic volcanos (Passaro et al., 2016) mostly made of pyroclastic rocks, such as Nisida island (3.92 ky BP, Fedele et al., 2015) and the Neapolitan Yellow tuff (NYT; De Vivo et al., 2001) and the Campanian Ignimbrite (CI; 39.28 ky BP, De Vivo et al., 2001) in the western part of the city of Naples. The most famous eruptions were the two largest caldera-collapse events of Campi Flegrei volcano. These eruptions emitted large volumes of magma that mantled extensive parts of city of Naples and reached the Sorrento Peninsula. This volcanic area is still active as testified by the recent eruption of Monte Nuovo in 1538 AD (Di Vito et al., in press; Guidoboni & Ciuccarelli, 2011).

The Somma – Vesuvius is a 1281 m-high stratovolcano, composed of the older volcano Mt. Somma and the younger cone Mt. Vesuvius, formed from the caldera collapses produced by the three main Plinian eruptions (Santacroce et al., 2008). The most famous of these eruptions is the 79 AD eruption that caused the burial of the Roman towns of Pompeii, Herculanum, and Stabiae.

These two large volcanic complexes are separated by two alluvial plains: the Sebeto and Sarno plains, mainly formed of pyroclastic fall deposits related to upper Pleistocene to Holocene volcanic activity, and alluvial deposits.

The present morphology of the gulf basin and its coasts has been influenced by the interaction between tectonics, volcanism and sea-level fluctuations that have greatly contributed to its evolution during the Quaternary cycle (Bruno et al., 2003; Cinque et al., 1997; Milia & Torrente, 1999, 2003, 2007).

### 3. Data and methods

The main coastal changes during the Holocene were evaluated by means of geoarchaeological surveys on several submerged archaeological sites (Mattei, 2016, Figure 2), conducted using two methods: integrated geophysical and morpho-bathymetric surveys by means of a marine drone (Giordano, Mattei, Parente, Peluso, & Santamaria, 2016).

Where possible, an integrated geophysical survey has been carried out using a seismo – stratigraphic system, a side scan sonar (SSS) morphological system and single beam echosounder bathymetric system. In the other cases, we have used the MicroVeGA drone, used to carry out surveys in very shallow water (Giordano, Mattei, Parente, Peluso, & Santamaria, 2015). A seismo-stratigraphic survey (sub-bottom profiler, SBP) was undertaken off the Seiano (Sorrento Peninsula, site 9 in Figure 2) pocket beach (Aucelli et al., 2016a, 2016b). In four other cases, seismo-stratigraphic profiles previously acquired were interpreted. This acoustic system is useful for detecting thin stratifications below the seabed as well as structures or artefacts buried (Figure 3(C)) by marine sediments (Mattei & Giordano, 2015). The D-Seismic system is high-resolution and discriminates facies in the order of 25–30 cm.

The bathymetric system used at six archaeo-sites was an Omex Sonar Lite Single Beam Echo Sounder (SBES) optimised for shallow water that measures the depth at centimetric precision.

The global positioning system (GPS) receiver used in all marine surveys was a Trimble DSM 232 GPS, with decimetric precision.

Finally, the MicroVeGA drone (used at five archaeo-sites) is an unmanned surface vehicle (USV) conceived, designed and built to operate in shallow-water areas (0–20 m), where a traditional boat is poorly manoeuvrable. Such as drone, engineered by the DIST research group at the Parthenope University of Naples, is a small and ultra-light catamaran with a draught of several centimetres, suitable for performing surveys up to the shoreline (Giordano et al., 2016). The payload of the MicroVeGA includes: (1) microcomputer; (2) differential GPS system and SBES; (3) integrated system for attitude control; (4) obstacle-detection system (SIROS1) with temperature control system; and (5) video acquisition system (both above and below sea level).

Moreover, at all sites studied, several direct surveys were carried out by a scuba driver in order to perform a clear interpretation of the archaeological markers and the correction of indirect data (Lambeck et al., 2004). Table 1 lists the survey techniques adopted and the related data obtained.

The Main map reconstructs the coastline evolution of the Gulf of Naples over the last 2000 years, but also includes the approximate positions of the coastline during the last glacial sea-level highstand (MIS 5) and the last glacial sea-level lowstand (LGM) as well as the maximum marine ingestion in the plains during the Holocene. The geographic information has been grouped as follows:

1. Geological legend including the main lithostratigraphic complexes;
2. Type of coast including the main geomorphological types;
3 Archaeological landscape including the main Roman settlements, the Roman streets and the Fontis Augustei Acquaeductum;
4 MIS 5 sea-level markers and coastline;
5 LGM coastline;
6 Holocene main coastal changes, including the coastline position during the maximum ingression (Cinque, 1991; Irollo, 2005), the archaeological sea-level markers, the vertical ground movements (VGM) measured at each archaeo-site (Aucelli et al., 2016a, 2016c; Cinque, 1991; Cinque & Irollo, 2008; Cinque et al., 2011; Romano et al., 2013), the horizontal movements of the coastline over the last 2000 years, a Valentin diagram summarising the main evolutionary steps of each coastal sector.

Finally, in each coastal sector the first century AD coastline has been reconstructed. In the case of the Vesuvius coast and Sarno plain, the position of the coastline predates the 79 AD eruption.

In order to better demonstrate the evolution of the coastline over the last 2000 years, a 3D view of three sectors (Posillipo – Napoli, box I on the map; Vesuvius and Sarno plain, box II on the map; Piano di Sorrento – Sorrento Peninsula, box III on the map) have been added as boundary...
information. The 3D views were obtained by interpolating the Light Detection and Ranging (LIDAR) data provided by the Ministry of Environment (0–200 m asl).

3.1. Geological legend

The main lithostratigraphic complexes have been represented by means of a polygonal geographic information system (GIS) layer (Figure 1) and have been organised as below:

- Shallow-water limestone and dolostone and flysch deposits of Mesozoic and Cenozoic age are represented in green;
- Pyroclastic fall, alluvial and slope deposits of the Upper Pleistocene – Holocene time-span related to the eruptive vents are represented in violet;
- Pyroclastic flows deposits of Campi Flegrei and Vesuvius volcanos (Upper Pleistocene – Holocene) are represented in orange;
- CI (39.28 ky BP, De Vivo et al., 2001);
- Lavas of Vesuvius related to the recent effusive activity (Santacroce & Sbrana, 2003).

3.2. Type of coast

Depending on the geological characteristics, the coasts of the Gulf of Naples were divided into five coastal stretches: Posillipo volcanic high coast, Chiaia and Sebeto coastal plains, Vesuvius volcanic high coast, Sarno coastal plain, Sorrento Peninsula high coast.

The coastal sectors, shaped over the last 2000 years by non-marine processes as river deposition, volcanic activity, tectonics and volcano-tectonic movements, are represented by a polyline GIS layer and have been divided as follows:

- Low coasts, including the Chiaia – Sebeto and Sarno coastal plains;
- Volcanic coasts, including the Posillipo and Vesuvius high coasts (this type represents coastal sectors of active volcanos mainly made of pyroclastic rocks and controlled by ground movements of volcanic origin);
High coasts with alternating pocket beaches, including the Sorrento Peninsula and Capri coasts.

### 3.3. Archaeological landscape

The anthropogenic landscape of the Roman period is represented on the map by the following layers, obtained from historical maps and reconstructions (Johannowsky, 1953, 1985; Keenan-Jones, 2010):

- main Roman settlements as a polygonal layer,
- Roman streets and the Fontis Augustei Aquaeeductum as polyline layers.

### 3.4. MIS 5 seal level markers and coastline

The MIS 5 coastline position on the map (Santangelo et al., 2017) coincides with the Marine Isotope Substage (MIS) 5.5, dated to between 132 and 116 ky (Shackleton, Sánchez-Góñi, Pailler, & Lancelot, 2003). The elevation of the MIS 5 sea-level markers (Ferranti & Antonioli, 2007; Ferranti et al., 2006, 2010) demonstrates a general subsiding pattern in the study area during this period, induced by regional tectonics and secondarily by soil compaction, with localised exceptional vertical ground movement related to volcanic processes.

### 3.5. LGM coastline

The coastline position during the last glacial period (60–15 ky) was influenced not only by marine regression but also by the CI eruption (39.28 ky BP, De Vivo et al., 2001), an extreme event that strongly modified the palaeolandscape. The pyroclastic flow of this eruption mantled the whole Gulf with deposits tens of metres thick, as demonstrated by the stratigraphic record in the plains (Aprile, Toccaceli, & Sbrana, 2004; Romano, Santo, & Voltaggio, 1994) and by seismic profiles in the offshore area (Milia & Torrente, 2007). The LGM coastline position, approximately coincides with the shelf break, between 140–180 m deep, demonstrating that the subsiding trend of the Gulf continued during this period (Milia & Torrente, 2007).

### 3.6. Holocene main coastal changes

The results of a series of geoarchaeological surveys performed on several submerged archaeological sites was integrated with bibliographic data (Aucelli et al., 2016a, 2016c; Cinque, 1991; Cinque & Irollo, 2008; Romano et al., 2013; Vogel & Märker, 2010), in order to increase the control points and to obtain the Holocene landscape evolution of the study area.

Non-invasive prospecting techniques have been used to investigate height underwater archaeological sites for the identification of the remains of man-made structures, as well as for a three-dimensional reconstruction of geomorphological and stratigraphic features linked to ancient positions and shapes of the coastline. All steps of the analysis were recorded within a GIS project structured in modules that managed both planning and processing data of the surveys (Mattei, 2010).

#### 3.6.1. Coastline position during the maximum  ingression

The coastline position during the maximum marine ingression related to the Holocene sea-level highstand (5.8 ky BP) was reconstructed in the coastal plain of Sebeto (Irollo, 2005) and Sarno (Cinque, 1991), by interpreting several stratigraphic records.

#### 3.6.2. Archaeological sea-level markers

The archaeological sea-level markers studied in each archaeo-site (Table 2) is represented on the map by a point symbol, classified as pier (including the quays), fishpond, building, breakwater, and archaeo-stratigraphic markers (such as buried beachface deposits). On the left part of the map, a photo of each archaeo-marker studied with the measurement of the first century sea level was represented in a table.

| Table 2. Sea-level markers studied in the 12 archaeo-sites. |
|---------------------------------|--------|----------------|------------------|------------------|
| Coastal sector ID Site Sea-level marker Reference |
|------|------|----------------|------------------|------------------|
| Napoli – Posillipo | 1 | Nisida port | pier | Unpublished data |
| Napoli – Posillipo | 2 | Gaiola | fishpond | Simeone and Masucci (2009) |
| Napoli – Posillipo | 3 | Marechiaro port | pier | Unpublished data |
| Napoli – Posillipo | 4 | Rosebery remains | building | Unpublished data |
| Napoli – Chiaia | 5 | Municipio excavations | Beach deposits | Unpublished data |
| Vesuvius | 6 | Herculaneum archaeo-site | Beach deposits (archaeo-stratigraphy) | Cinque and Irollo (2008) |
| Vesuvius | 7 | Terma Ginnasio | breakwater | Unpublished data |
| Sarno | 8 | Sarno | Beach deposits (archaeo-stratigraphy) | Cinque (1991) |
| Sorrento Penisula | 9 | Seiano | pier | Aucelli et al. (2016b) |
| Sorrento Penisula | 10 | Sorrento | fishpond | Aucelli et al. (2016b) |
| Sorrento Penisula | 11 | Capo Sorrento | pier | Aucelli et al. (2016b) |
| Sorrento Penisula | 12 | Punta Campanella | pier | Aucelli et al. (2016b) |
3.6.3. First century AD coastline

The production of morphological data has allowed the precise evaluation of coastal evolution over the last 2000 years and the Roman coastline position (Aucelli et al., 2016a, 2016c; Cinque, 1991; Cinque & Irollo, 2008; Irollo, 2005; Romano et al., 2013), as well as a 3D reconstruction of the emerged and submerged landscape. This output for all archaeo-sites using the high precision bathymetric survey, was integrated with a digital terrain model of the adjacent coastal stretches obtained by processing coastal LIDAR data provided by the Italian Ministry of the Environment in March 2013. On the map, we have reconstructed the 3D morphology of three coastal sectors, derived from the LIDAR data, and the position of the Roman coastline derived from the bathymetric data.

3.6.4. Vertical ground movements

The submersion of all archaeological markers (S) was calculated by correcting the measurement taken by the SBES with respect to the tide and atmospheric pressure (Leoni & Dai Pra, 1997), in order to evaluate the submersion with respect to the present mean sea level. This value was then added to the functional height (H) or depth at the time of the building (Auriemma & Solinas, 2009) – in order to obtain the relative sea-level rise over the last 2000 years ($\Delta SL$).

Finally, the vertical ground movement (Figure 4) affecting the archaeological site studied was calculated as:

$$\Delta z = \Delta SL - E,$$

where $\Delta SL$ is the sea-level change (m) over the last 2.0 ky; $E$ is the value (m) of the eustatic curve taken from Lambeck et al. (2011: 1.088 m) in Figure 4.

On the map, the circles at the archaeological sites represent the measured VGM, the colour defines the direction and the dimension defines the amount.

3.6.5. Horizontal movements of coastline

The late Holocene evolution of each coastal sector inferred from geoarchaeological data was the target of this work. Moreover, coastline evolution over the last 2000 years was achieved by the evaluation of $\Delta SL$, namely sea-level rise due to the eustatic effect added to sea-level oscillation due to vertical ground movement affecting each coastal stretch. In the case of a high coast, we positioned the hypothetical ancient coastline of a specific coastal stretch on the isobath corresponding to the value of $\Delta SL$ evaluated at all archaeo-sites studied in the sector, and then we evaluated the horizontal variation. In the case of a low coast, the coastline position was obtained by interpreting published stratigraphic data or by interpreting seismic profiles (as in the case of the Seiano pocket beach).

The bathymetric measurements taken at all archaeological sites were integrated with the multibeam bathymetric map provided by Servizio Difesa Suolo – Regione Campania, CARG project.

On the map, the horizontal arrows quantify the horizontal movements of the various sectors, and the colour defines the main forcing.

3.6.6. Valentin diagram

A graphic summary of the effects of endogenous and exogenous factors on the coasts evolution is given by the Valentin Diagram (1952), which consists of two graduated axes (expressing the average rates of the processes) that, crossing the zero
point, become four semi-axes and define four quadrants (Figure 5).

The vertical axis is the change in relative sea level, namely the algebraic sum of the absolute rate of change in the average sea level and the rhythm of VGM.

The horizontal axis is the prevailing morphodynamic trend of the coastal stretch, linked to the alternating periods of erosion and deposition.

On the map, a sketch of this diagram was constructed for each coastal sector, summarising the main steps of coastal evolution over the last 2000 years; the colour of the circles defines the age of the steps.

4. Discussion and conclusions

The landscape evolution map of the coasts of the Gulf of Naples has the aim of representing the relative sea-level changes and modification of coastal landscape that has occurred since the Roman period, by means of a geoarchaeological study of several submerged archaeological sites, but also coastline evolution between the last interglacial sea-level highstand and the last glacial sea-level lowstand. In addition, the maximum marine ingression in the two coastal plains during the Holocene has been marked with the approximate position of the coastline at that time.

The coast of the Gulf of Naples over the last 2000 years has had a diverse evolution depending on outcropping lithology and VGM, as well as the arrival of primary or secondary pyroclastic flows on some coastal stretches, as in the case of the 79 AD eruption of Vesuvius.

In the map presented here, the evolution of the coastal landscape in each coastal sector has been reconstructed by evaluating the VGM that has occurred over the last 2000 years, of volcano-tectonic origin (connected to the activity of Campi Flegrei and the eruption of Vesuvius in 79 AD) or due to regional tectonic forcing.

The Neapolitan coastal sector has been affected by a subsiding trend that has led to the submersion of the Posillipo coastal sector because of eustasy and of regional tectonic phenomena (Romano et al., 2013).

The Vesuvian coast has been greatly affected by volcano-tectonic VGM and has been strongly modified by the effects of the Plinian eruption of Vesuvius in 79 AD (Cinque & Irollo, 2008).

In the Sebeto and Sarno coastal plain a subsiding trend, partially due to regional tectonics and the compaction of loose sediments, was compensated by substantial clastic contributions related to the emplacement and reworking of pyroclastic products of the Vesuvius volcano (Irollo, 2005; Vogel & Märker, 2010 and references therein).

Finally, the Sorrento Peninsula is a tectonically stable sector with submerging coasts, although some stretches of coastline have been modified by flooding following the 79 AD Vesuvius eruption (Aucelli et al., 2016a, 2016c).

We must highlight the fundamental role that the Plinian eruption of Vesuvius in 79 AD has played in the modification of the south-eastern coastal landscape of the Gulf. In fact, both pyroclastic flows, and the subsequent floods, have caused abrupt coastal advance of several hundred metres, not only in the Vesuvius coastal sector but also in some pocket beaches of the Sorrento Peninsula.

In this map we summarise these results and in particular:

- The horizontal arrows quantify the horizontal movements of the various sectors, and the colour defines the main forcing.
- The circles on the archaeological sites represent the measured VGM, the colour defines the direction.
- The schematic Valentin diagrams summarise the main evolutionary steps of the various coastal areas, the colour of circles define the age of the steps.

In conclusion, this map by offering geological, geomorphological and archaeological data may represent a state-of-the-art for scientists working in these fields. This product is a useful cartographic tool to understand the coastal changes over the investigated time-span and related main causes. Therefore, it represents the first level of information for scientists that want to investigate the relationship between human and coastal environments in the past. It also provides much information, such as VGM and relative sea-level rise that can be used for studies on coastal trend predictions, as well as the impacts of climate change.

Software

The main data layers were created using Esri ArcGIS: lithostratigraphic complexes, coastal types, coastlines, geoarchaeological data. The Spatial Analyst extension was used to interpolate the bathymetric data and to create the shaded relief of the base map, deriving from the mosaic of 5×5 m DTM provided from Campania Region. The final layout in A1 format was produced using CorelDRAW.

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**ORCID**

Gaia Mattei https://orcid.org/0000-0003-4582-3265

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