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Marine Environments in Front of the Ancient City of Pompeii (Southern Italy) at 79 CE: New Insights for the Unknown Location of the Harbour

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Abstract: A multidisciplinary study, including geomorphological, stratigraphic, paleontological and archaeological methods and techniques, allowed for a detailed exploration of coastal landforms and environments in front of the ancient city of Pompeii (southern Italy). The famous site of Pompeii sits on a small volcanic hill in the alluvial-coastal plain of the Sarno River, very close to the ancient paleoshoreline. When the Roman city was buried during the eruption of Vesuvius in 79 CE, pyroclastic fall and flow deposits covered the urban centres and ancient coastal landforms. In this study, 83 new boreholes were carried out up to a depth of 10 m. Some of them (15) were analysed for their sedimentological, stratigraphical and paleontological characterisation, in order to reconstruct the sedimentary environments in 79 CE. The data collected allow for new hypotheses to be formulated regarding the paleoshorelines, as well as the 79 CE coastal landforms and environments. In particular, litho-stratigraphic and fossil assemblages highlight the presence of shallow marine environments in a large back-ridge depression, named Masseria Curati, that is located just outside the city walls. This hypothesis opens new insights on the unknown location of the harbour of the Roman city.

Keywords: geoarchaeology; geomorphology; paleoenvironmental studies; coastal landforms; mediterranean ancient harbours

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Citation: Aiello, G.; Amato, V.; Amoretti, V.; Barra, D.; Di Vito, M.A.; Doronzo, D.M.; Infante, A.; Russo, A.; Sparice, D.; Zuchtriegel, G. Marine Environments in Front of the Ancient City of Pompeii (Southern Italy) at 79 CE: New Insights for the Unknown Location of the Harbour. *Land* **2024**, *13*, 1198. https://doi.org/10.3390/land13081198

Academic Editors: Michelle Devlin, Paulette Posen, Naomi Greenwood and Carlos Campos

Received: 28 June 2024
Revised: 30 July 2024
Accepted: 31 July 2024
Published: 4 August 2024

1. Introduction

The Roman city of Pompeii is famous for its destruction in 79 CE, when Vesuvius awoke explosively, producing one of the largest eruptions of its history. The city was buried under several metres (4–6 on average) of volcanic products consisting of fall and pyroclastic current deposits [1–3]. Buildings were destroyed, and the inhabitants were killed by building collapses or died by asphyxia or thermal impact due to fine particle load and the temperature of pyroclastic currents [4–9]. For many centuries, Pompeii slept beneath its layers of ash and pumice, which perfectly preserved the remains. In the 1700s, these were finally partially unearthed, and the world caught a tantalising glimpse of a Roman city "fossilised" in time. The main public buildings discovered included the forum, theatres, temples and amphitheatre, as well as private lavish villas and all kinds of houses, some dating back to the 4th century BCE; however, several suburban structures (including the harbour) are still not identified. It seems certain that Pompeii was first settled by Oscan and Etruscan inhabitants [10], then strategically urbanised and built on a relic of an ancient volcanic hill, close to the Tyrrhenian Sea at the mouth of the Sarno River [11–14]. The paleogeographic and paleoenvironmental reconstructions of the Sarno alluvial-coastal plain, and in particular of the Pompeii coastal landforms, play a key role in understanding the birth, development, rise, decline and disappearance of this important ancient city and its infrastructure. The choice of location of the settlement was a direct consequence of the coastal and volcanic landforms in the alluvial coastal plain. In particular, the development and rise of the urban layout were related to the proximity of the coastline, while the decline and social crisis were not only related to political and socio-economical factors but also to the alteration of the coastline, volcanic eruptions and volcano-tectonic movements (earthquakes and ground uplift) [12,14,15]. The disappearance of a number of Roman towns in the Vesuvian area was due to them being buried under the pyroclastic deposition by fall and flow processes that acted during the Plinian eruption of 79 CE [16–18]. The eruption buried the 79 CE ground surface and landforms with up to 5 m of pumice and ash layers, causing the total destruction of the ancient towns of Pompeii, Stabiae, Oplontis and Hercolaneum [10]. At the same time, the layers of the eruption allowed for the preservation of the 79 CE environments and landforms, especially in the coastal and alluvial plain sectors.

A detailed geomorphological study, based on a 1:5000 topographic map (contour lines of 1 m) was carried out in order to identify ancient environments and landforms of the coastal sector of the Pompeii site. The study highlighted the occurrence of a morphological depression (ca. 5 m a.s.l.) located between the ancient dunal ridges and the anxient city of Pompeii, which are still preserved despite being buried by 79 CE deposits.

In this area, we analysed archeo-stratigraphical data from the literature [11,19–27] and obtained new stratigraphical and paleoenvironmental data from 83 new boreholes and trenches. Better detail of the drilled successions was given to the layers covered by 79 CE deposits, in order to identify ancient environments (e.g., marine, shallow marine, marshy, fluvial, etc.) and their distribution along the Pompeii coastal sector. The layers just below the 79 CE deposits were sampled and analysed in detail for their paleontological contents (ostracoda, foraminifera, etc.). This multidisciplinary approach allows us to distinguish between 79 CE marine, shallow marine, marshy and fluvial environments, as well as paleosols and anthropogenic deposits. Being shallow marine environments localised in the central sector of the morphological depression, named Masseria Curati, very close to the Pompeii city gates (Porta Marina and Porta Stabiae), we used these paleoenvironmental data to hypothesise on the unknown location of the harbour, comparing it with other available data from the literature [25,28–40].

2. Previous Knowledge on Coastal Environments and Landforms

The ruins of Pompeii are located in the central-northern area of the Sarno River alluvial coastal plain, close to the southern slope of Vesuvius (Figure 1a). The ancient city was built on the relics of an ancient volcanic edifice, named Pompeii Volcano [11], interpreted as the result of the coalescence of craters and volcanic landforms, whose activity is not directly related to that of the Somma-Vesuvius volcano. The period of activity of the Pompeii Volcano is constrained to the Late Pleistocene, and more precisely to the time interval between 40 ka and 20 ka [11,41] (Figure 1a(1)). Also, in the urban area, several volcanic landforms were recognised [11,13].

On the Tyrrhenian Sea front, the Pompeii Volcano flanks were cut by sea waves of the transgressive phase of the Early Holocene sea-level rise [23]. A steep cliff up to 15 m was created on the western and southern flanks of the volcanic hill (Figure 1a(1)). After the transgressive phase, the Pompeii hill and the alluvial coastal plain were under the control of different morphogenetic and sedimentary processes. In particular, Early Holocene coastal evolution was strongly controlled by the interplay between a decrease in sea level rise [42] and volcano tectonic movements, and for historical times, also by anthropogenic changes.

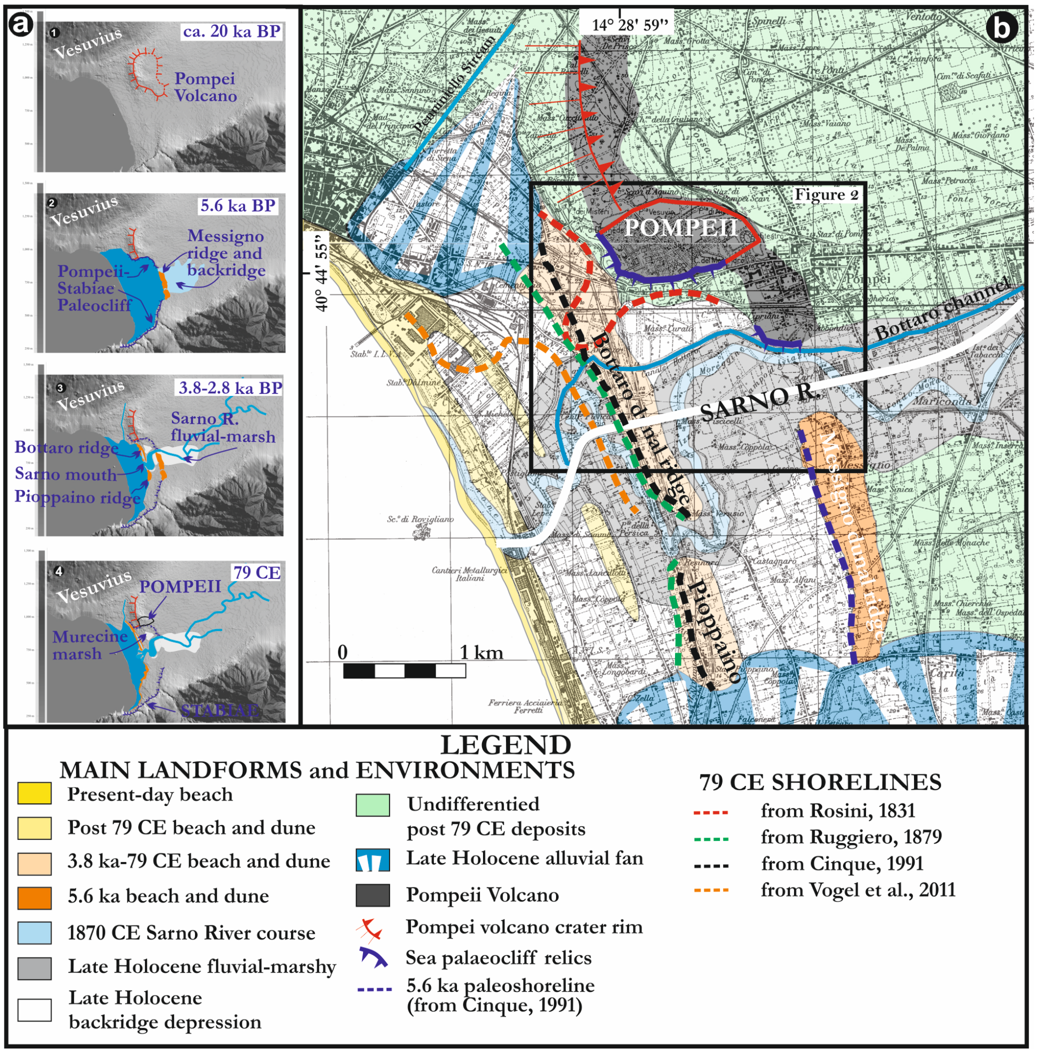

Figure 1. Holocene landforms and environments inferred by the literature data in the Sarno River alluvial plain: (**a**) sketches of the main Late Pleistocene-Holocene evolutionary stages; (**b**) 1:25,000 geological map and 79 CE paleoshoreline hypotheses from various authors: Rosini 1831 [19], Ruggiero 1879 [20], Cinque 1991 [23], Vogel et al. 2011 [27]. The black line box represents the available data on harbour location reported in Figure 2. 1:25,000 map was adapted with permission from [43].

Since the end of 1700 CE, several geologists and archaeologists tentatively proposed various hypotheses on the coastal, lagoonal, marshy and fluvial environments, and on the location of the paleoshoreline in 79 CE. In particular, the coastal sector in front of Pompeii was investigated, in order to reconstruct the coastal landforms and paleoenvironments and their evolution during the Late Holocene period (Figure 1b).

Regarding the position of the ancient shorelines [19], it is hypothesised that the 79 CE shoreline was very close to the western and southern parts of the ancient city, with coastal landforms consisting of two wide bays (Figure 1b, dashed red line).

An alternative hypothesis was suggested by [20], which, adopting archaeological and geological approaches, proposed a paleoshoreline more pronounced (Figure 1b, dashed green line) with respect to that drawn by [19]. In addition, the author hypothesised the locations of the ancient fluvial mouths of the Sarno River.

Between 1970 and 1980, researchers from the Earth Science Department of the Federico II Naples University demonstrated, by drilling about 70 deep boreholes, that the coastal zone of the Sarno River was composed of three orders of barrier-lagoonal systems, roughly parallel to the present-day shoreline and decreasing in age from the inner part outwards towards the sea [21–24] (Figure 1b). These studies identified an inner dunal ridge (the Messigno ridge) in the southern area of the coastal plain, which was ^{14}C dated at 5.6 ky BP (Figure 1a(2)). Lagoonal and shoreface environments reached the central part of the coastal plain, creating a pronounced gulf within the plain (Figure 1a(2)). On the other hand, in the northern part of the plain, the fast sea level rise that occurred in the Early Holocene formed steep cliffs on the slopes of Somma-Vesuvius and along the southern and western flanks of the Pompeii Volcano [11]. Another dunal ridge (the Bottaro ridge in the northern part of the plain and Pioppaino in the south) was identified a few hundred metres to the south (Figure 1a(3),b). Its age was established to be c. 3.8 ka–2.8 ka BP through radiocarbon dating. In the area between the Messigno and Pioppaino dunal ridges, in the southeastern part of the plain, and between the Pompeii paleocliff and the Bottaro dunal ridge, in the northwestern part, a lagoonal environment developed. The paleocourses of the Sarno River were identified within the back-ridge depressions as large and wide meanders, one of which went as far as the Moregine area and continued a few kilometres further south (Figure 1b). These authors proposed a more detailed position of the 79 CE shoreline confirming roughly the hypothesis of [20] (Figure 1b, dashed black line, and Figure 1a(4)). More recently [27], thanks to new stratigraphical data from boreholes and geomorphological study using a Digital Terrain Model, a more advanced shoreline position than those proposed by [21–24] has been hypothesised (Figure 1b, dashed orange line).

Previous Knowledge on the Harbour Location

Several historical and archaeological studies [28–31] hypothesised that the coastal harbour was located in front of the Bottaro dunal ridge or within the inlet of the ridge (Figure 2).

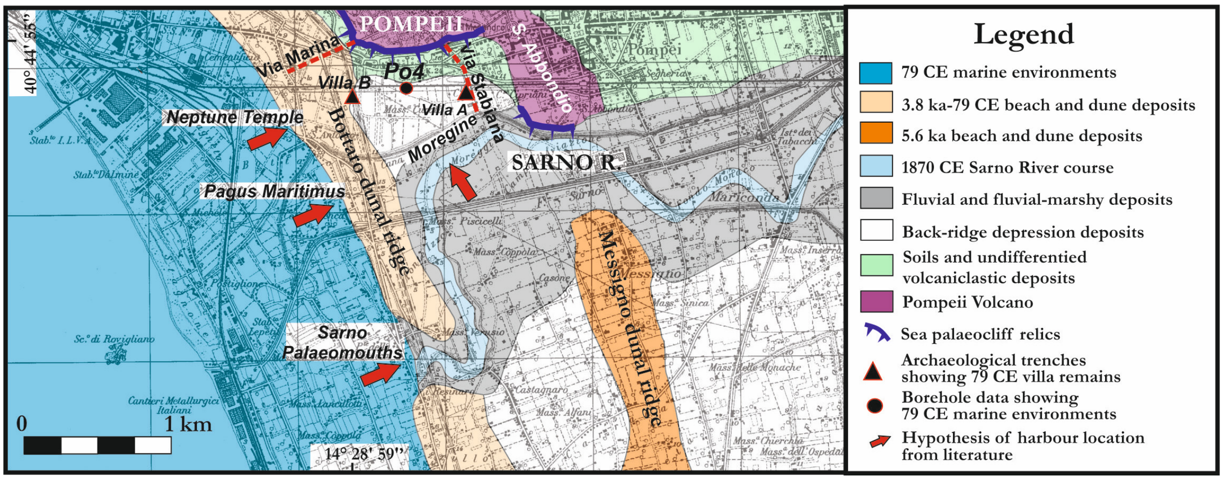

Figure 2. The 79CE coastal landforms with the location of the archaeological sites and the hypothesised positions (red arrows) of the harbour areas. Coastal landforms after [22,23]. A and B are Roman sites located out of the urban area, P04 is the borehole of [39]. 1:25,000 map was adapted with permission from [43].

In fact, Ref. [39] hypothesised the presence of a lagoonal or fluvial-lagoonal harbour in the area between Porta Stabia and Porta Marina, just outside the southern part of the ancient city. He identified shallow marine sands buried by the 79 CE pyroclastic fall deposits within a borehole (Po4 in Figure 2). On the other hand, further studies [32–37] placed the harbour within or in proximity of the ancient fluvial mouth of the Sarno River. More recently, Ref. [25] also placed the 79 CE ancient harbour within the fluvial mouth of the Sarno River, based on historical and archaeological data supported by borehole data. However, the authors did not support their data with accurate facies analyses of the sediments buried by the 79 CE deposits. The interpretation of the lithofacies in particular was not supported by paleontological analyses. Other studies located the ancient harbour within the Sarno River course, in correspondence with the archaeological excavation at the Moregine site [38] (Figure 2).

3. Materials and Methods

3.1. Geomorphological and Paleoenvironmental Approaches

In order to improve the knowledge on the main landforms of the Pompeii coastal sector, a geomorphological study was carried out starting from the analysis of 1:5000 topographic maps [43–45] and integrated by field surveys using new altimetrical acquisitions using GPS instruments (Trimble Geo 7X). This integrated approach enabled us to draw a new map with 1 m contour lines (Figure 3a).

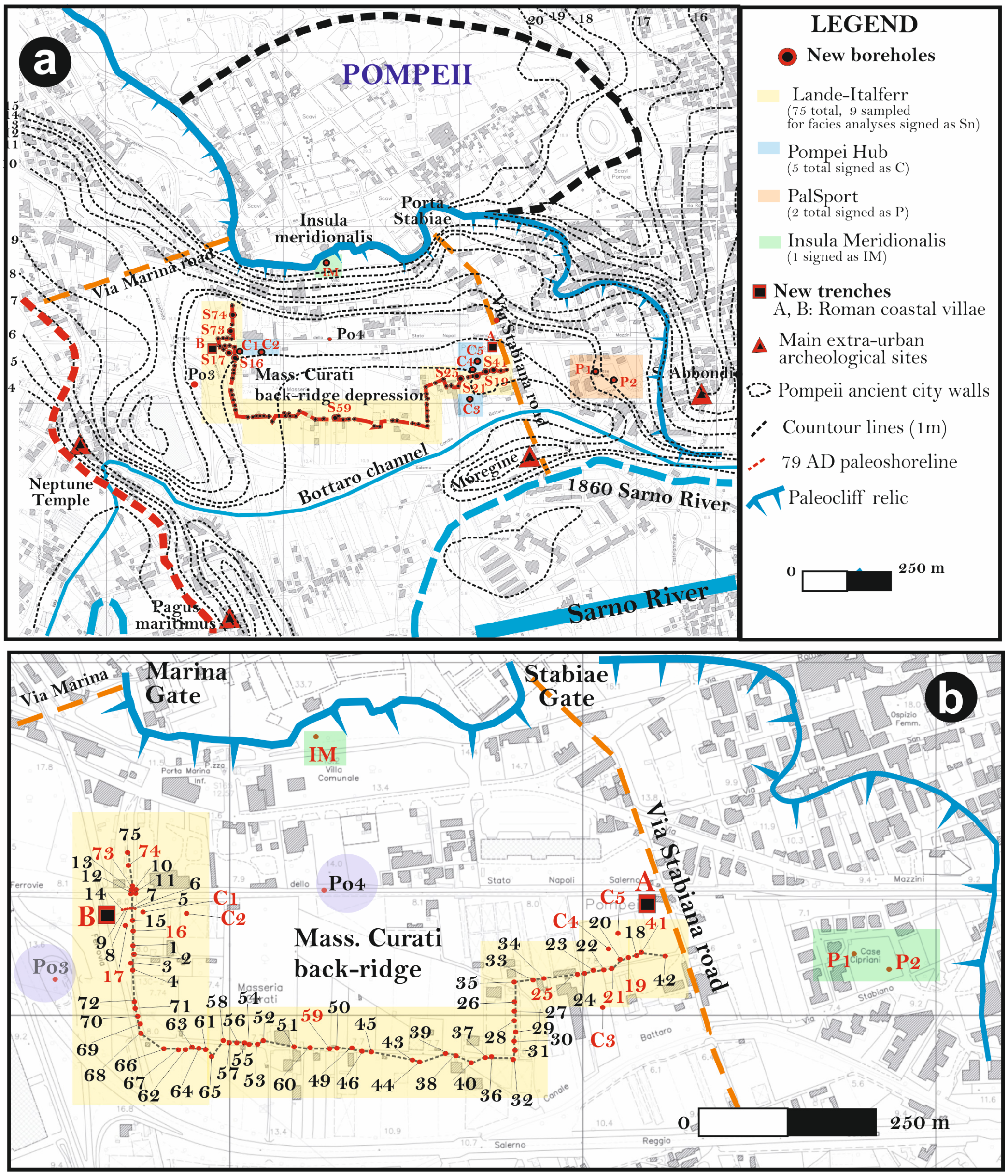

Figure 3. Contour line reconstruction (at 1 m intervals) on 1:5000 regional map showing the locations of the stratigraphical and paleoenvironmental data (new boreholes and archaeological trenches) (**a**). Also highlighted on the map: the 79 CE shoreline, the early Holocene cliff, 1860 and the present-day course of the Sarno River as well as the location of the main extra-urban archaeological sites and roads. A detail of borehole (signed as 1–75, C1–C5; P1–P2, IM and Po4) and trench locations (signed as A and B) used in this work (**b**).

The boreholes reached a depth up to 10 m and were made within the back-ridge depression of Masseria Curati. Most of them were made in 2013 by Lande-Italferr (75), then in 2021 by Pompei Hub (5), Pompei PalSport (2) and Insula Meridionalis Project (1) [46].

The various layers of the drilled successions were analysed and described directly in the field in terms of colour, texture (grain size, shape and composition) and sedimentary and diagenetic structures, according to the methods of [47,48] for facies classification in SUs (stratigraphic units) and following the methodologies for Unconformity Boundary Stratigraphic Units [49]. This approach allows us to highlight the preliminary interpretation of the facies and their related paleoenvironments.

Such interpretation was complemented by the recognition of fossil and biological remains. Several samples were collected in both borehole and trench stratigraphic successions, in order to extract data on paleontological assemblages (foraminifer tests, ostracod shells and other meiofaunal fossil remains).

The chronology of the various lithofacies was mainly derived according to the rich archaeological content and to the presence of the tephra layers of the 79 CE eruption of Vesuvius [2,16,50,51]. These layers were easily recognisable both in the boreholes and archaeological trenches, as part of the well-studied 79 CE pyroclastic succession around Vesuvius up to more distal reaches [3,17,18,52]. They consist of basal white to grey pumice lapilli fall deposits, on average 2 m thick, overlaid by stratified ash and lapilli deposits (up to 2 m) emplaced by pyroclastic currents and reworked volcaniclastic deposits. In each analysed stratigraphic succession, we paid particular attention to those layers directly sealed by the 79 CE deposits, because they could have been potentially rich with paleoenvironmental clues relative to the 79 CE eruption. Critically, additional data were obtained by reviewing any other available stratigraphic and paleoenvironmental data from the literature, so as to extract useful information about the paleoenvironments and coastal configuration [11,20,22,24–27,53,54].

The geomorphological study was supported by facies analysis and chronological characterisation of 83 new boreholes and archaeo-stratigraphic trenches (Figure 3a,b).

3.2. Paleoecology

Paleoecological analyses were performed on 34 samples as follows: 3 from the IM core (Insula Meridionalis), 31 samples collected from 9 cores (S16, S17, S19, S21, S25, S41, S59, S73 and S74) in the Lande/Italferr sampling site (20 samples), 5 cores (C1–C5) in the "Pompei HUB" sampling site (9 samples) and 2 cores (P1–P2) in the PalSport site (2 samples).

The sediment samples (100 g dry) were oven-dried, disaggregated in boiling water with sodium carbonate, washed through 230 and 120 mesh sieves (63 and 125 µm, respectively) and then examined under a reflected light microscope.

In particular, quantitative analyses were carried out on benthic foraminiferal and ostracod assemblage abundance values, consisting of the total number of foraminiferal specimens, ostracod Minimum Number of Individuals (MNI) and ostracod Total Number of Valves (TNV). MNI is the greater number between the right and left adult valves plus the number of adult carapaces. When only young instars were recorded, the MNI equals one. TNV includes all the juvenile and adult valves. Bivalves and gastropods (mostly as fragments), charophyte oogonia, echinoderm spines, serpulid tubes, diatoms, radiolarians, sponge spicules and plant remains are reported as semiquantitative data.

Benthic foraminiferal and ostracod taxa were identified according to the classic and modern literature both for the benthic foraminifers and ostracods [55–58] and references therein.

All the studied specimens are housed in the Aiello-Barra Micropaleontological Collection (ABMC) at Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli Federico II.

4. Results

4.1. Coastal Landforms in Front of Pompeii Ancient City

The reconstruction of the contour lines (Figure 4) shows that the Pompeii coastal area is composed of very articulated ancient landforms, despite some of them being completely masked by thick 79 CE pyroclastic deposits and post-79 CE reworked and pedogenised volcaniclastic deposits.

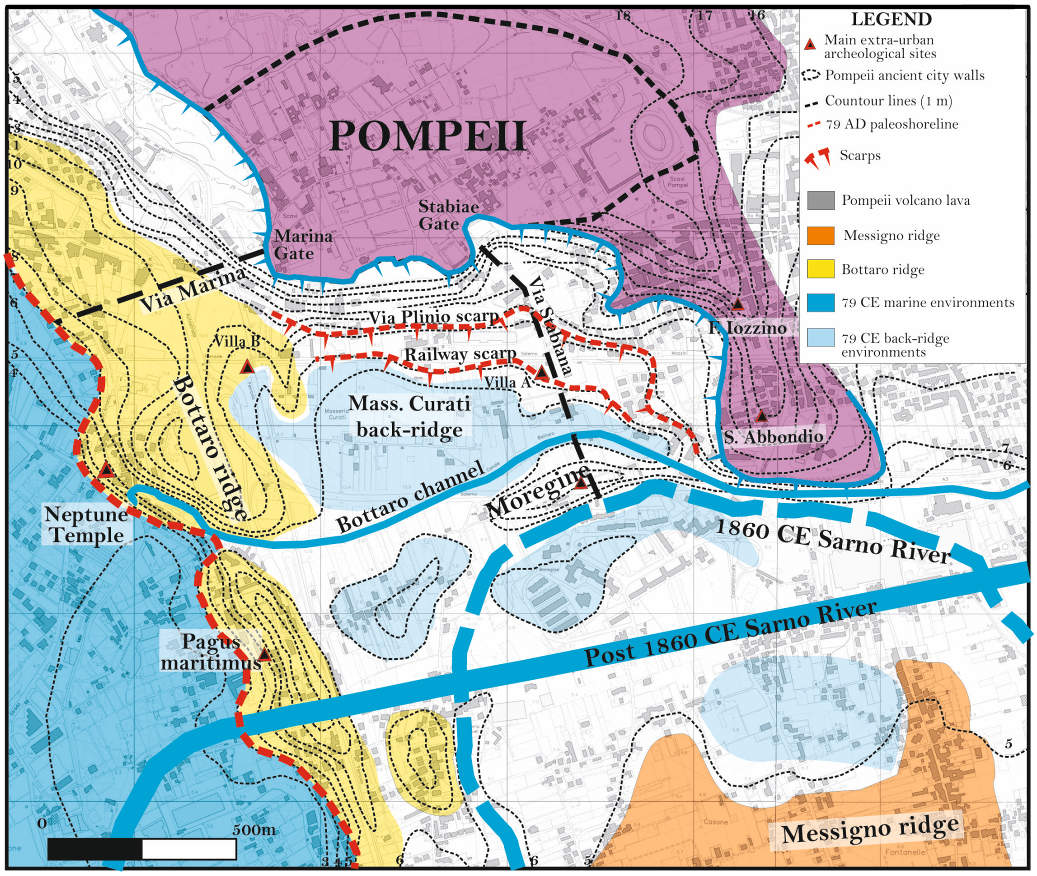

Figure 4. Geomorphological map of the Pompeii coastal zone in 79 CE.

First of all, contour lines confirm that Pompeii city was built on the relics of an ancient volcanic edifice, whose southern flanks were cut by sea waves of the transgressive phase of the Early Holocene sea level rise, according to [11,23]. A steep cliff up to 15 m was created on the western and southern flanks of the volcanic hill (Figure 4).

Towards the Tyrrhenian Sea, downslope of the paleocliff, 79 CE coastal landforms are still recognisable. They are constituted by NW-SE aligned little ridges, that are relics of ancient dunal systems, presenting flanks with different slopes: the SW flanks are steeper than NE. At the base of the SW slope, according to previous studies [22,27], the 79 CE shoreline can be hypothesised. This is also supported by archaeological data along the ancient coastline, as the Temple of Neptune and Pagus Maritimus are built on the ancient beach, to the north and to the south, respectively [59] (Figure 4).

The NE flanks connect gently with the flat depressed sectors (between 5 and 7 m a.s.l.), which can be interpreted as back-ridge depressions. A back-ridge sector, located between the Pompeii paleocliff and Bottaro coastal ridges, named Masseria Curati back-ridge depression, was investigated in detail in this work. Our data demonstrate that the depression was partially occupied by shallow marine environments in 79 CE, and for this reason, it can be referred to as an ancient paleolagoon/paleomarsh.

The coastal ridge, named Bottaro ridge, consists of two main hills that reach c. 12 m a.s.l. They are separated by the Bottaro channel, an artificial channel built three centuries ago to divert water from the Sarno River to power water mills. It is not possible to exclude the notion that the Bottaro channel was constructed using a more ancient channel (Roman channel?). If data suggesting that an older (Roman?) channel was exploited to construct the Bottaro channel are realistic, as testified by archaeological data [59], it is reasonable to assume that the more ancient channel was built to create a connection between the sea and the back-ridge depression of the Masseria Curati. Other remains of dunal ridges are present in the southern part of the Pompeii coastal belt, in the inner part of the coastal plain, where the relic of the Messigno prehistoric ridge is still recognisable (Figure 4). Geomorphological approaches allow us to hypothesise that the ancient paleocourse of the Sarno River ran between the San Abbondio lavic hill and Messigno dunal ridge, very close to the position of the 1860 CE paleocourse. The geomorphological data, supported also by stratigraphical data [60], allow us to exclude the possibility that the Sarno River paleocourse ran across the area of the San Abbondio hill close to the southern city walls, as hypothesised by [37], or ran close to the Insula Meridionalis as hypothesised by [40].

In the area between the Bottaro dunal ridge and Pompei paleocliff (Figure 4), the northern border of the Masseria Curati back ridge depression was marked by two little scarps (2–3 m high). A first scarp runs across the road of via Plinio (Via Plinio scarp) between the 8 and 7 m contour lines, while a second scarp runs across the Railway track (Railway scarp) between the 6 and 5 m contour lines. We do not know the origin of these two scarps, i.e., whether they were due to tectonics, coastal erosion or also artificially created. It is reasonable to think that these scarps constituted two important anthropic elements of the Pompeii coastal sector and consequently they divided different environments of the urbanised territory. For these reasons, in our opinion, they were artificially created before 79 CE. In fact, archaeological data confirm that above the Railway scarp, the territory was densely inhabited and occupied by villas, roads, channels and other anthropic builds, while the area just below the escarpment (Masseria Curati depression) was uninhabited until 79 CE [61,62]. No archaeological evidence is known from this area, which is also confirmed by recent archaeological excavations for the Pompei Hub Project. The archaeological remains completely surround the area of depressions. To the northwest, a Roman maritime villa was excavated ten years ago (Villa A in Figure 4) (from Sistema Informativo Pompei) [61,62], while to the northeast, a Roman factory was excavated over ten years ago (Villa B in Figure 4) (from Sistema Informativo Pompei) [61,62]. In addition, two important roads, the via Marina and via Stabiana, are located in the western and eastern parts of the depression.

4.2. Stratigraphical Data

4.2.1. Previous Stratigraphic Data

A critical review of previously published stratigraphic data was carried out. In the Supplementary Materials Table S1, a synthesis of both stratigraphical and paleoenvironmental data from 51 boreholes and trenches is presented. Their location (Figure 5) and paleoenvironmental interpretation allow us to better define the reconstruction of the shoreline at 79 CE in the Pompeii coastal sector.

The 79 CE back-ridge shallow marine environments were recorded in the following boreholes: P03 and P04 of [11]; DAI6 of [53]; and 2, 3, 15, 16, 17, 19 and 32 of [22].

In the Masseria Curati back-ridge depression, only P03 and P04 recorded shallow marine environments, allowing us to delimit the depression towards the north and west, respectively.

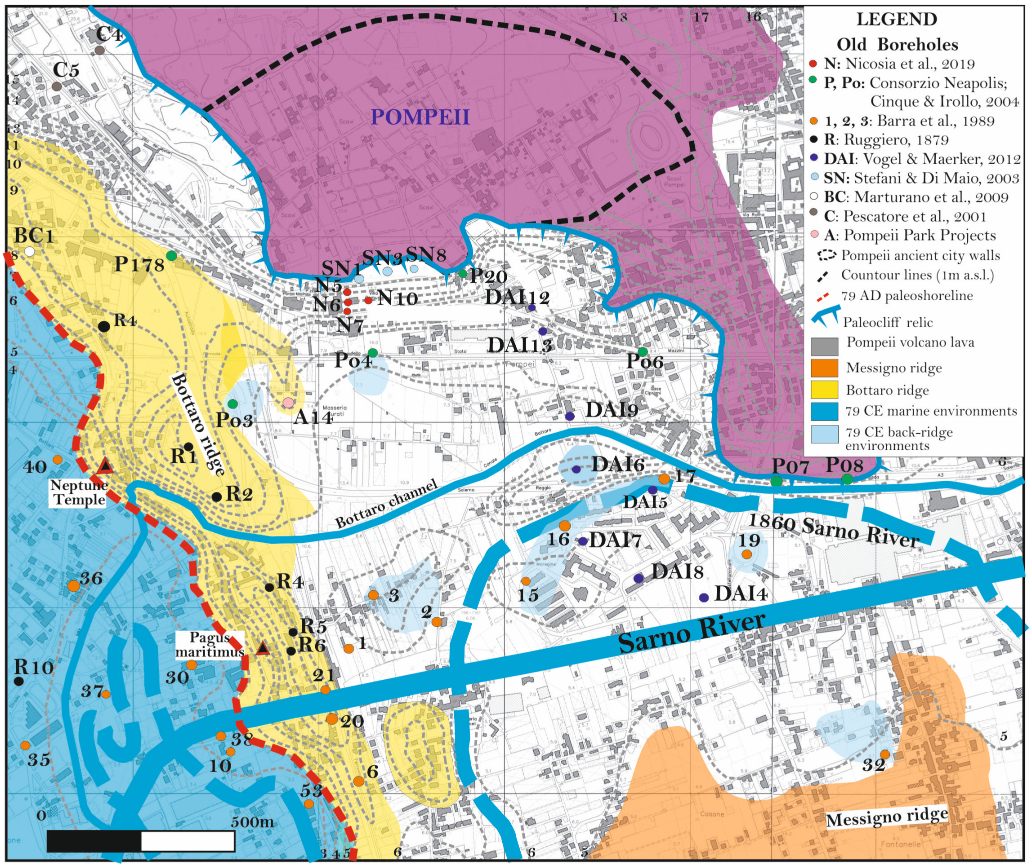

Figure 5. The 79 CE geological map (1:5000) based on previous paleoenvironmental studies and geomorphological approach. (Nicosia et al. 2018 [26], Consorzio Neapolis [43], Cinque & Irollo 2005 [11], Barra et al. 1999 [22], Ruggiero 1879 [20], Vogel & Maerker 2012 [53], Stefani & Di Maio 2003 [25], Marturano et al. 2009 [54], Pescatore et al. 2001 [24]).

4.2.2. New Borehole Data from the Masseria Curati Back-Ridge Area

In the area of the Masseria Curati back-ridge depression, 83 new borehole stratigraphies are available (Figure 3b; Table 1).

A total of 75 of them (labelled from S1 to S75) were made in 2013 for the construction of the new Railway. Among these, nine were analysed in detail for paleoenvironmental, tephrostratigraphical and chronological information: four boreholes (S74, S73, S16 and S17) from the western part of the depression, one (S59) from the central area and four (S19, S21, S25 and S41) from the eastern part.

In addition, eight new boreholes were made in 2019 for the realisation of the Pompei HUB railway project (labelled from C1 to C5), for the creation of the new sports centre (Palazzetto dello Sport Project) (labelled as P1 and P2) and for geotechnical purposes (Insula Meridionalis Project, labelled as IM) (Figure 3b). C1 and C2 boreholes are located in the western sector and C3, C4 and C5 in the eastern sector of the Masseria Curati depression, while P1 and P2 are located just outside (eastern part) of the depression, between the Sant'Abbondio paleocliff and the via Plinio scarp. IM is located very close to the Pompeii ancient paleocliff. In the C1–C5, P1–P2 and IM boreholes, only the layers buried by the 79 CE pyroclastic deposits were sampled for micropaleontological analyses.

The main stratigraphical features of the boreholes (10 m depth) are presented in Table 1 and shown in Figure 6, while paleontological contents are presented in Tables 2–4 and SEM micrographs of some shallow marine microfossil remains are shown in Figure 7. Stratigraphical details of the 83 boreholes are synthesised in Supplementary Materials Table S2.

Table 1. Main stratigraphical features and paleoenvironments of the borehole units.

Unit	Facies Description	Environment
1	Brown and grey-brown volcaniclastic sandy deposits with a great amount of heterogenous and heterometric clastic components	Anthropogenic infilling
2	Dark-brown volcaniclastic fine sands with a great amount of organic matter (as little roots, wood) and coarse volcaniclastic contents as light pumice and dark lithics.	Soil and reworked volcaniclastic deposits
3	Several stratigraphical units can be synthesised into two main subunits: (3a) Greyish sandy-silt compacted ash, massive to the top and laminated to the bottom with intercalations of light pumice and dark lithics. This subunit, emplaced by pyroclastic currents, can be correlated to the phreatomagmatic phases of the 79 CE eruption, and to the most widespread pyroclastic current deposits in the eruption (corresponding to unit EU4 and EU8 of the volcanological stratigraphic framework of the 79 CE pyroclastic sequence by [1]). (3b) Openwork subangular loose pumice, grey to the bottom and white to the top, with inclusions of rare lithics, scoriae and yellowed carbonatic clasts. This subunit correlates to the Plinian fall deposits of the eruption (corresponding to unit EU2 and EU3 of [1]).	79 CE eruptive units
4	Dark-brown volcaniclastic fine and medium sands, silty clay matrix supported, very rich in organic matter, both widespread within sediments both as remnants of charcoal, wood and bones. The top of the buried soil is marked by a thin reddish layer that also includes little calcified and weathered roots. An archaeological content (ceramics, bricks, fine pottery and tiles), with both angular and smoothed forms, is also present. Generally, the interface between this unit and the underlying unit is gradual. Several samples were taken for facies analyses (Tables 3 and 4). The samples are devoid of significant microfossils, though one sample contains a rare continental species.	79 CE buried soil
5	Dark-brown loose volcaniclastic fine-medium to medium-coarse sands very rich in widespread and weathered organic content. Millimetric shell fragments, rounded and subrounded millimetric carbonatic clasts and charcoal are also present. Several samples have been taken within the cores and subjected to paleontological analyses, allowing us to interpret this unit as an upper infralittoral environment (or upper shoreface) (Tables 3 and 4).	79 CE shallow marine deposits
6	Loose medium-coarse volcaniclastic sands, strongly rounded. The unit contains a centimetric ash and little pumiceous tephra layer, probably correlatable with fall-out deposits of the Somma-Vesuvian interplinian activity between the Avellino eruption (3.9 ka) and 79 CE. The paleoecological analyses of several samples taken in this unit reveal a lack of significant fossils. Many samples are barren or contain few freshwater species.	Fluvial deposits
7	Medium-coarse and medium-fine volcaniclastic sands with a dark-grey silty matrix very rich in organic content. Several shell fragments and charcoal are also present. This unit can be referred to as infralittoral environments as testified by the fossil assemblage.	Marine deposits
8	Porphyritic leucitic lava presenting a light alteration to the top.	Lava bedrock

Table 2. Data synthesis for paleontological assemblage of the analysed sample.

Borehole	Sample Depth (m)	Fossil Contents	79 CE Paleoenvironments
S16	7.10–7.20	very rare gastropod fragments	buried soil
S17	7.80–8.00 8.10–8.20	rare gastropod fragments, echinoderm spines and rare siliceous sponge spicules	mediolittoral (foreshore)
S19	4.80–5.00 5.40–5.50 5.80–5.90 6.40–6.50	well-diversified marine assemblages including benthic foraminifers, ostracods and other metazoan remains	upper infralittoral (upper shoreface) 0–5 m b.s.l., except the sample 5.80–5.90: mediolittoral (foreshore) ~0 m (~sea level)
S21	4.70–4.90 5.20–5.30	rare gastropod fragments and rare diatoms fragments; microscopic remains of various marine taxa	mediolittoral (foreshore) ~0 m (~sea level)
S25	4.80–4.90 5.20–5.30 5.60–5.70	benthic foraminifers, gastropod and echinoderm spines	upper infralittoral (upper shoreface) 0–5 m b.s.l., except the sample 5.20–5.30: mediolittoral (foreshore) ~0 m (~sea level)
S41	4.30–4.40 4.40–4.60 5.10–5.30 5.30–5.50 5.50–5.70	rare gastropod fragments; marine taxa including gastropods, benthic foraminifers and echinoderm spines	mediolittoral (foreshore) ~0 m (~sea level) except the sample 5.50–5.70: upper infralittoral (upper shoreface) 0–5 m b.s.l.
S59	5.70–5.80	barren	buried soil
S73	7.10–7.20	gastropod fragments	buried soil
C1	5.80–5.90	barren	buried soil
	5.90–6.00	gastropods and plant remains	
C2	5.85–5.90	barren	buried soil
	6.00–6.10	gastropods and plant remains	
C3	5.50–5.60	gastropods and plant remains	buried soil
C4	5.90 6.70–6.80	gastropods and plant remains	buried soil
C5	5.30–5.40 6.00–6.10	barren	buried soil
P1	SA1	plant remains	buried soil
P2	SA2	plant remains	buried soil
IM	3.50 7.00	barren	buried soil
	4.60	microscopic plant remains	

Table 3. Paleontological contents of the analysed samples. The yellow columns represent samples of shallow marine environments, taken immediately under 79 CE pyroclastic deposits (VR = very rare; R = rare; U = uncommon; C = common, A = abundant).

Borehole	S16	S17		S19				S21		S25			S41					S59	S73	S74
Samples	7.10–7.20	8.10–8.20	7.80–8.00	6.40–6.50	5.80–5.90	5.40–5.50	4.80–5.00	5.20–5.30	4.70–4.90	5.60–5.70	5.20–5.30	4.80–4.90	5.50–5.70	5.30–5.50	5.10–5.30	4.40–4.60	4.30–4.40	5.70–5.80	7.10–7.20	6.10–6.20
BACILLARIOPHYTA																				
BIVALVIA					R		R						VR	VR	R					
ECHINODERMATA			VR				R		VR	VR	R				VR					
GASTROPODA	VR		R	VR	U	U	VR	C	U	A	A	R	R	A	C	R	VR	barren	U	barren
PORIFERA		VR			VR		R	VR	VR											
RADIOLARIA									VR											
SERPULIDAE				VR	VR	VR	VR	R	VR											
FORAMINIFERA																				
Ammonia aberdoveyensis (Haynes 1973) [63], rounded form													1							
Cibicides lobatulus (Walker & Jacob, 1798) [64]										1										
Elphidium poeyanum (d'Orbigny, 1839) [65], FS form										2			2							
Gavelinopsis praegeri (Heron-Allen & Earland, 1913) [66]												1						barren		barren
Neoconorbina terquemi (Rzehak, 1888) [67]				1																
Rosalina macropora (Hofker, 1951) [68]							1													
Rosalina obtusa (d'Orbigny, 1846) [69]						1														
Tretomphalus concinnus (Brady, 1884) [70]						1														
OSTRACODA MNI																				
Loxoconcha ovulata (Costa, 1853) [71]						1														
OSTRACODA TNV																				
Loxoconcha ovulata (Costa, 1853) [71]						1														

Table 4. Data synthesis for paleontological assemblage of the analysed sample (VR = very rare; R = rare; U = uncommon; C = common).

Borehole/Trench	SA		C1		C2		C3	C4		C5		IM		
Samples	SA1	SA2	5.80–5.90	5.90–6.00	5.85–5.90	6.00–6.10	5.50–5.60	5.90–6.00	6.70–6.80	5.30–5.40	6.00–6.10	3.50	4.60	7.00
GASTROPODA			barren	VR	barren	VR	VR	C	VR		barren	barren		barren
PLANT REMAINS	R	VR		VR						U			VR	

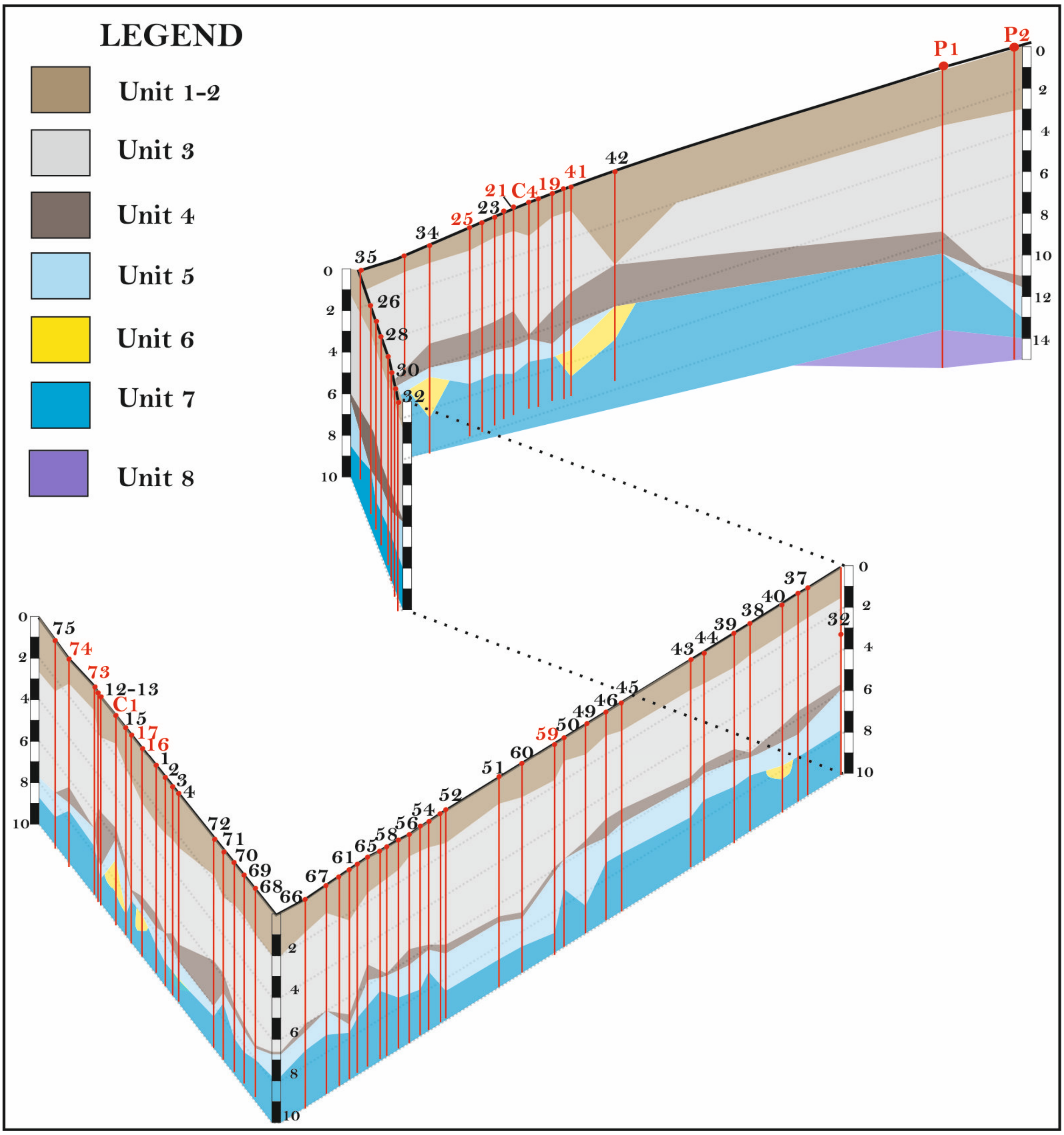

Figure 6. Stratigraphical data from investigated boreholes. Red boreholes are those analysed also for paleoecological contents.

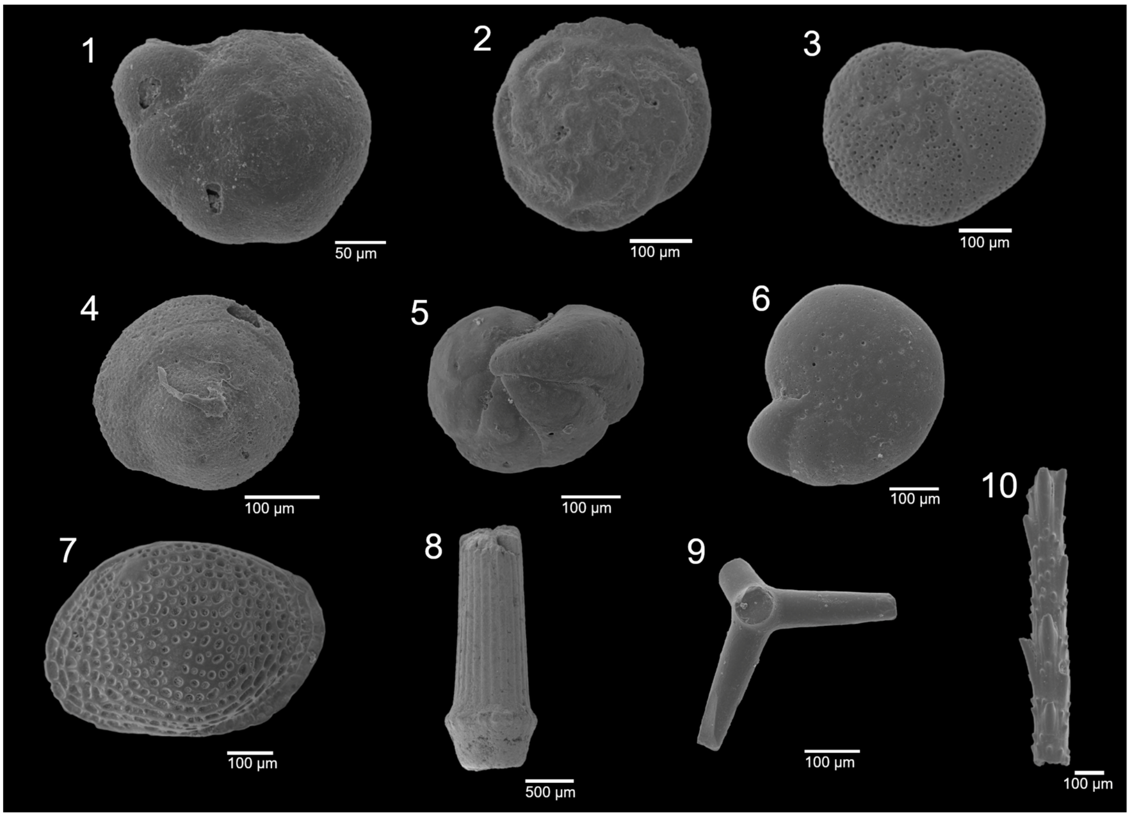

Figure 7. SEM micrographs of microfossil remains. The figured taxa are characteristic of upper infralittoral marine environment. (1) *Ammonia aberdoveyensis* (Haynes 1973 [63]) rounded form, spiral side, sample S41 5.5–5.7, ABMC 2020/095; (2) *Rosalina macropora* (Hofker 1951 [68]), spiral side, sample S19 4.8–5.0, ABMC 2020/096; (3) *Rosalina obtusa* (d'Orbigny 1846 [69]), spiral side, sample S19 5.4–5.5, ABMC 2020/097; (4) *Neoconorbina terquemi* (Rzehak 1888) [67], spiral side, sample S19 6.4–6.5, ABMC 2020/098; (5) *Cibicides lobatulus* (Walker and Jacob, 1798) [64], spiral side, sample S25 5.6–5.7, ABMC 2020/099; (6) *Elphidium poeyanum* (d'Orbigny 1839) [65], FS form, side view, sample S41 5.5–5.7, ABMC 2020/100; (7) *Loxoconcha ovulata* (Costa 1853) [71], left valve, sample S19 5.4–5.5, ABMC 2020/101; (8) echinoderm spine, sample S17 7.8–8, ABMC 2020/102; (9) sponge spicule, sample S19 4.8–5.0, ABMC 2020/103; (10) echinoderm spine, sample S19 4.8–5.0, ABMC 2020/104.

From the bottom to the top, we distinguished eight stratigraphic units:

Unit 8: Lava bedrock. Only P1–P2 and IM boreholes intercepted the lavic unit of the Pompei Volcano.

Unit 7: Marine environments. All boreholes intercepted sands very rich in organic content and shell fragments. This unit can be referred to as infralittoral (upper shoreface) environments, as testified by the fossil assemblage recognised in the sample picked within S19, S25 and S41.

Unit 6: Fluvial environments. C1–C4, S16, S17, S19, S34, S40 and S41 boreholes intercepted thin layers of coarse volcaniclastic sands, strongly rounded in fluvial environments, also containing a centimetric tephra layer, probably correlatable with fall-out deposits of the Somma-Vesuvian interplinian activity that occurred between the Avellino eruption (3.9 ka) and 79 CE [72]. The paleoecological analyses of several samples taken in this unit reveal a lack of significant fossils. Many samples are barren or contain few freshwater species.

Unit 5: Marine environments. Almost all boreholes intercepted sands very rich in organic content and millimetric shell fragments. Fossil assemblage shows environments from mediolittoral (foreshore) to upper infralittoral (upper shoreface), representative of a water depth ranging from 0 to 5 m (Tables 3 and 4). In the S17, S19, S21, S25 and S41 boreholes, shallow marine environments are just below the 79 CE eruptive layers, while in a great part of the boreholes, the contact between volcanic layers and marine sediments is marked by reddish oxidation layers, thin paleosols and anthropogenic layers very rich in potteries, stones, tiles and other archaeological materials.

Unit 4: Paleosols and anthropogenic layers made of potteries, stones, tiles, ceramics and bricks.

Unit 3: 79 CE volcaniclastic layers. All the boreholes intercepted the pumices and ashes of the fall and pyroclastic density current deposits related to the 79 CE eruption. The thickness is variable from 4 to 6 m.

Units 1 and 2. Post-79 CE reworked colluvial deposits, buried and modern soils.

5. Discussion

The collected borehole data allow us to infer the presence of shallow marine environments (from upper infralittoral or upper shoreface to mediolittoral or foreshore) in 79 CE within the back-ridge depression of Masseria Curati. In detail, in the S17, S25, S21 and S19 boreholes, the 79 CE eruption products sit directly on top of deposits of shallow marine environments. In the S16, C1, C2, C3 and C4 boreholes, the 79 CE pyroclastic fall deposits lie on marine sandy silts that present some faint traces of pedogenesis towards the top. The pedogenesis of these marine deposits at the borders of the Masseria Curati back-ridge depression probably started only a few years before the 79 CE eruption. It could be the consequence of vertical movements of the ground uplift that preceded the eruption.

In order to evaluate the extension of the shallow marine environments and tentatively plot their boundaries, we take also into account the paleoenvironmental data from old boreholes available in the literature. In particular, the P03 and P04 boreholes show that the 79 CE products lie on marine environment deposits [11]. On the other hand, other boreholes (signed as B, N and SN in Figure 5) show that the 79 CE pyroclastic products lie on soils, fluvial and fluvial-marshy deposits. Consequently, the shallow marine environments should have been concentrated in the more depressed area of the back-ridge depression between the Bottaro sandy dunal ridge and the Pompeii–Stabiae road, toward the east (Figure 8a).

Towards the north, the extension of the marine paleoenvironments is limited by the railway scarp and by stratigraphical and paleoenvironmental data of available boreholes (N of [39] in Figure 5). Towards the south, the shallow marine environments did not cross the Bottaro channel and the archaeological area at Moregine.

In the eastern area, the edge of the shallow marine environments runs between the S19 and S41 boreholes, while in the western area, it runs between the S17 and S16 boreholes, because in both the S41 and S16 boreholes, the 79 CE sediments lie on buried soils and pedogenised marine deposits. In addition, available archaeological data allow us to confirm that to the east, the shallow marine environments did not reach beyond the via Stabiana and the Roman villa (A in Figure 8a), while to the west, they were limited by the steep scarp and remnants of the Roman villa (B in Figure 8a).

The presence of shallow marine environments in the area between the Bottaro back-ridge and the ancient city of Pompeii opens a new scientific debate on the coastal configuration at the time of the 79 CE eruption of Vesuvius, particularly due to the connection of the Masseria Curati back-ridge depression with the sea. With these data, we can establish that this back-ridge depression was occupied by shallow marine environments in 79 CE and that its extension was wider until a short time before 79 CE, probably up to the Railway scarp because stratigraphical data of the layers covered by the 79 CE eruptive units are made of pedogenised marine sands (C3, C4, C5 and 41 boreholes).

The presence of shallow marine environments in the M. Curati back-ridge depression behind the Bottaro dunal ridge allow us to hypothesise that it must be connected with the sea. Where are these connections located?

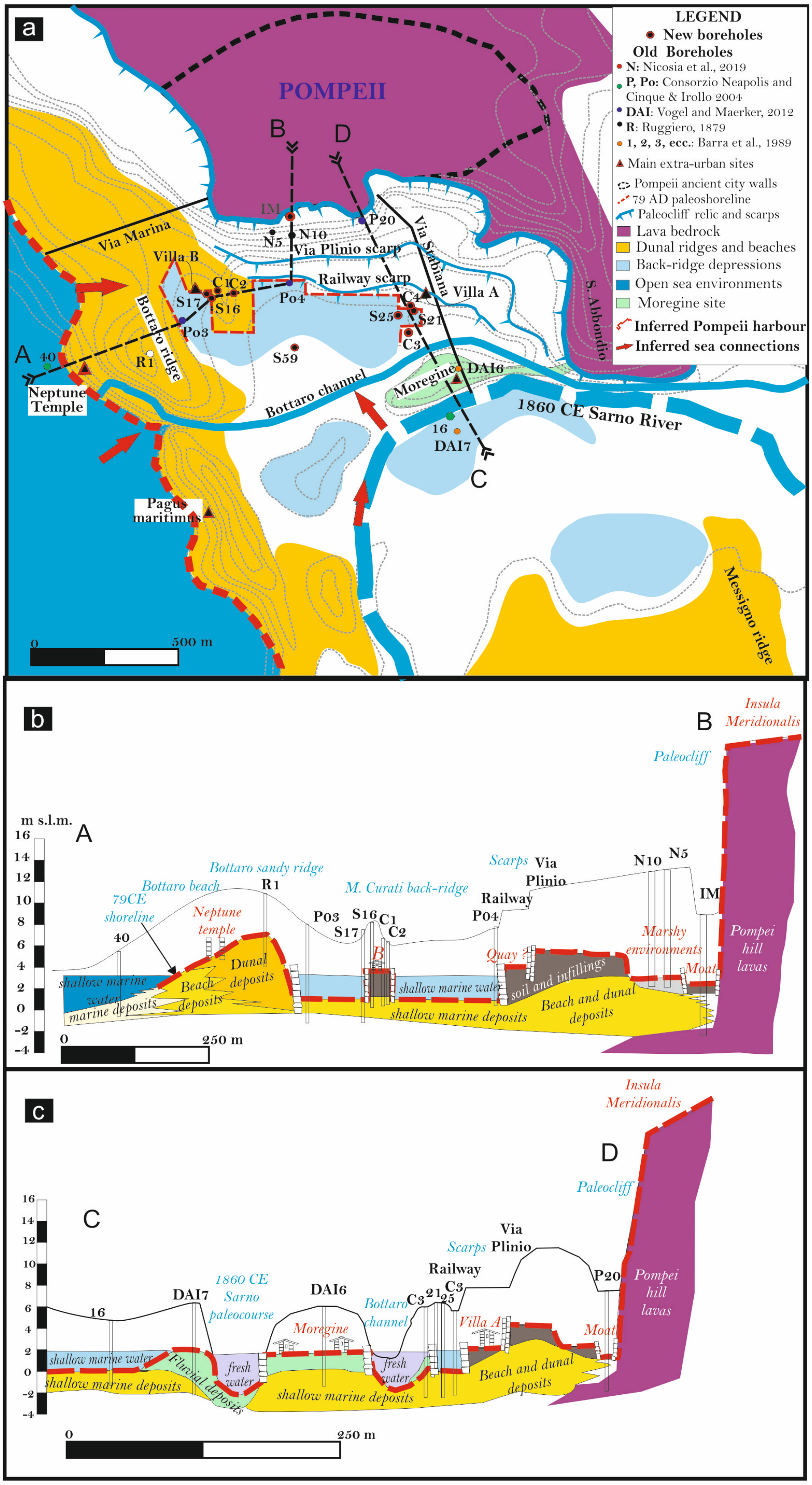

Figure 8. Inferred paleogeographical reconstruction of the Pompeii coastal area in 79 CE (**a**) and geological schematic cross-sections (AB and CD) passing through more significative archeo-stratigraphical and paleoenvironmental data (**b**,**c**). (Nicosia et al. 2019 [26], Consorzio Neapolis [43]; Cinque & Irollo 2005 [11]; Vogel & Maerker 2012 [53]; Ruggiero 1879 [20]; Barra et al. 1999 [22]).

More hypotheses can be formulated (red arrows in Figure 8a):

- ➢ The Bottaro dunal ridge presented one or more morphological discontinuities to allow the marine waters to reach to the Masseria Curati area.
- ➢ Artificial channels may be hypothesised, too, as often demonstrated at other back-ridge depressions also hosting Roman harbours [73,74], with references therein. It may have run between the Bottaro channel, Bottaro mill and the Temple of Neptune where today there is an artificial channel.
- ➢ Other possible connections can be hypothesised north of the Bottaro dunal ridge, where it drops in height, or in the southern area where the ancient Sarno River paleomouth cuts the dunal ridge at several points.

The data presented open a new research potential for the characterisation of the coastal environments near the ancient city of Pompeii in 79 CE, and consequently addresses the issue of the location of the harbour. In terms of the harbour, besides the data from the literature conjecturing that it lay along the Sarno River or near its paleomouth(s), we suggest that the harbour could also be located in the Masseria Curati back-ridge depression, that locally had shallow marine environments with a water depth that also reached ca. 5 m, as testified by fossil assemblage. To support this hypothesis, there is a complete lack of archaeological sites and structures in the Masseria Curati depression and an absence of significant archaeological findings in the analysed boreholes and trenches. This absence could be due to environments being unsuitable for human habitation and conducive to commercial and productive marine sites such as harbours, salt marshes or fish farms, although this last suggestion was hypothesised to have occurred several hundred meters to the north [75,76].

With the hypothesis that the harbour of Pompeii was located in the Masseria Curati depression, it is possible to explain several issues: (1) Shallow marine environments, very close to the city gates of Porta Stabia and Porta Marina, must have been very important locations for commercial and productive activities. Little boats and floats could have navigated these environments presenting a sea level ranging from 0 to 5 m, or this area could have been a salt marsh with fish farms. (2) The Railway scarp can be interpreted as an old quay or as an edge of the shallow marine environment until a few years before 79 CE. Progressively, this edge might have shifted towards the south, likely due to the vertical movements of the ground level that preceded the 79 CE eruption. (3) The back-ridge depression was surrounded by archaeological remains that form an almost rectangular shaped area, which could confirm the hypothesis that the coastal landforms were anthropogenically modified in Roman times (Figure 8b,c). In addition, the Masseria Curati depression was perfectly bordered by two very important roads: the via Stabiana to the east and via Marina to the west. (4) The shape of the inferred harbour was particularly well defined, with a quay within the Bottaro dunal ridge, the Via Marina road between P04 and S17 boreholes and another little quay in the eastern area between the S1–S5 and C3–C4-S19 boreholes (Figure 8b). (5) The connection to the open sea could have been regulated by openings (natural or artificial channels) either in the Bottaro ridge, probably very close to the Temple of Neptune or the site of Pagus Maritimus, or alternatively by the Moregine settlement that was very close to the Sarno River mouth (Figure 8c). The site at Moregine can also be interpreted as a complex that controlled the opening and access to the shallow marine environments.

These data are not conclusive proof that the harbour was located in the Masseria Curati back-ridge depression, but they clearly allow for the hypothesis of shallow marine environments within a large part of the depression itself. Further investigations (boreholes, geophysics, etc.) need to be undertaken, particularly in the central and more depressed area of the back-ridge, in order to shed light on the exact location of the harbour near the ancient city of Pompeii.

6. Conclusions

It is very difficult to reconstruct the coastal landforms and environments around the ancient city of Pompeii because the 79 CE ground level was buried by over 5 m of fall and pyroclastic current deposits. On the other hand, borehole and deep-trench stratigraphic data allowed us to reach those buried levels (and related environmental features) that characterised the coastal zone of Pompeii in 79 CE. The multidisciplinary research presented, based on stratigraphic and palaeoecological borehole data supported by some geomorphological evidence, allows us then to formulate a new hypothesis regarding the 79 CE paleoshoreline as well as the coastal landforms and environments. The results support the presence of shallow marine environments in a large back-ridge depression, the Masseria Curati, located to the southwest of the city of Pompeii in 79 CE. In particular, a focused synthesis of all data, which also takes into account available stratigraphic and paleoenvironmental data known in the literature and archaeological data, allows us to hypothesise that the Massera Curati back-ridge depression was bordered to the north by anthropogenic coastal landforms, nowadays testified by two little scarps (the via Plinio and Railway scarps). The presence of Roman villas and roads (via Marina and Via Stabiana) in the eastern and western areas and the available stratigraphic data outline a large rectangular area of shallow marine environments that can be placed in a chronological interval shortly before the 79 CE eruption. Upper shoreface and foreshore environments, characterised by a sea level ranging from 0 to 5 m and testified by fossil assemblage, allow for the hypothesis of this area being used for small harbours, landing places, quays and other maritime structures or, alternatively, as salt marshes or fish farms. These hypotheses bring new insights into a possible harbour location of the ancient Roman city, opening up the potential for new multidisciplinary research into the uses of this area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13081198/s1, Table S1: Stratigraphical data from available boreholes and trenches. The table shows (2rd and 3th colums) the paleoenvironmental data of the layers just below 79 CE eruption and their relative m a.s.l. Table S2: Stratigraphical data synthesis of the analyzed boreholes. Grey filling of the column represents 79 CE eruptive unit, light-green color lines represent boreholes with paleoecological interpretations, light-yellow lines represents boreholes with 79 CE marine environments. Bold red text are layers with high content of archaeological remains.

Author Contributions: In particular, V.A. (Vincenzo Amato) conceived the paper, analysed the data and wrote the first and revised versions of the manuscript. Paleontological analyses and/or sample preparation were accomplished by G.A., D.B. and A.I.; tephrostratigraphical analyses were carried out by M.A.D.V., D.M.D. and D.S.; archaeological setting was accomplished by V.A. (Valeria Amoretti), A.R. and G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors are grateful to Massimo Osanna from the Pompeii Archaeological Park, for supporting this research and to Sophie Hay for critically reviewing both of the contents and English form of the manuscript. The authors are also grateful to three anonymous referees for their useful suggestions and comments that fully improved the paper.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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