

Article

The Subsurface Geology and Landscape Evolution of the Volturno Coastal Plain, Italy: Interplay between Tectonics and Sea-Level Changes during the Quaternary

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Abstract: The Volturno alluvial-coastal plain is a relevant feature of the Tyrrhenian side of southern Italy. Its plan-view squared shape is due to Pliocene-Quaternary block-faulting of the western flank of the south-Appennines chain. On the basis of the stratigraphic analysis of almost 700 borehole logs and new geomorphological survey, an accurate paleoenvironmental reconstruction before and after the Campania Ignimbrite (CI; about 40 ky) eruption is here presented. Tectonics and eustatic forcing have been both taken into account to completely picture the evolution of the coastal plain during Late Quaternary times. The upper Pleistocene-Holocene infill of the Volturno plain has been here re-organized in a new stratigraphic framework, which includes seven depositional units. Structural analysis showed that two sets of faults displaced the CI, so accounting for recent tectonic activity. Yet Late Quaternary tectonics is rather mild, as evidenced by the decametric vertical separations operated by those faults. The average slip rate, which would represent the tectonic subsidence rate of the plain, is about 0.5 mm/year. A grid of cross sections shows the stratigraphic architecture which resulted from interactions among eustatic changes, tectonics and sedimentary input variations. On the basis of boreholes analysis, the trend of the CI roof was reconstructed. An asymmetrical shape of its ancient morphology—with a steeper slope toward the north-west border—and the lack of coincidence between the present course of the Volturno River and the main buried bedrock incision, are significant achievements of this study. Finally, the morpho-evolutionary path of the Volturno plain has been discussed.

Keywords: well log correlation; late Quaternary environments; sea-level changes; Volturno plain; southern Italy

1. Introduction

The Tyrrhenian coast of Italy is edged by several coastal plains separated by more or less pronounced promontories, especially in its southern segment. In northern Campania, the region of Naples, one of the major alluvial-coastal plains is that of the Volturno River (Figure 1), characterized by a regular (i.e., roughly quadrangular) shape due to the regional-scale Pliocene-Quaternary block-faulting of the western flank of the southern Appennines, accompanying the back-arc basin opening.

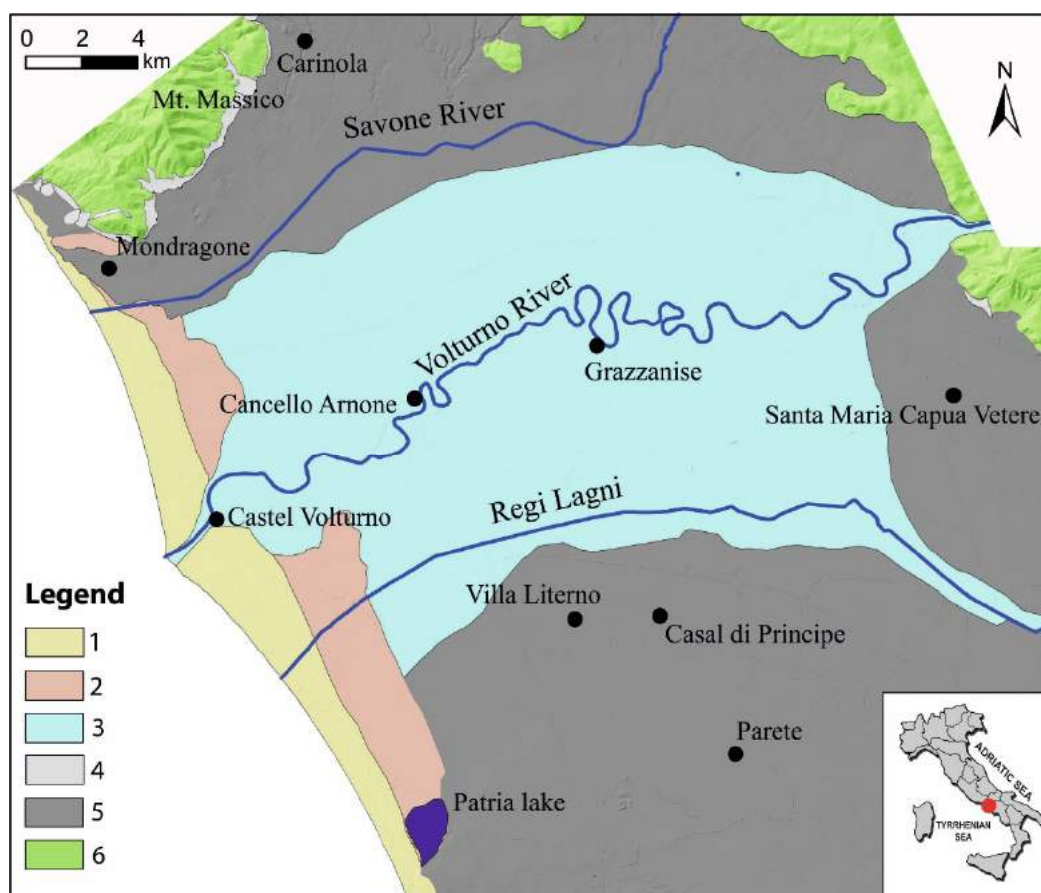


Figure 1. Simplified geological map of the Volturno Plain area; Legend: (1) dunal ridge deposits (Holocene); (2) marsh deposits (Holocene); (3) alluvial deposits (Late Pleistocene-Holocene); (4) slope waste deposits (Late Pleistocene-Holocene); (5) lavas and pyroclastic rocks of Roccamonfina Volcano, Phlegraean Fields, and Mt. Somma-Vesuvius (Middle Pleistocene-Holocene); (6) Pre-Quaternary bedrock.

The Volturno plain is bordered by the structural highs of Mt. Massico and Caserta Mts. to the north-west and north-east, respectively, and by the Ischia Island-Phlegraean Fields volcanic areas to the south-east. This coastal plain has been widely studied in the past, mostly from a stratigraphic viewpoint, defining the basin architecture by means of borehole analysis [1–8]. The aim of our work is to improve the number of observations of archives of boreholes (as yet partly unpublished), investigating the stratigraphy of the Quaternary infill of the plain on the basis of almost 700 well logs, so better reconstructing some trends in subsurface markers. In addition, the geomorphological analysis of the Late Quaternary landscape (mainly coastal features and foothill–plain connecting landforms) has been performed to complete the framework of the recent evolution of the plain. The final goal of this study is in fact to define a detailed paleoenvironmental and stratigraphic reconstruction after the well-known Campanian Ignimbrite (hereafter CI) eruption. In particular, we try to reveal how and when the tectonic subsidence was active during the last sea level rise in the study area, also characterized by relevant variation of sediment supply. It is worthy to note that kilometers-thick successions of marine, transitional, and alluvial sediments, besides great numbers of volcanic rocks, filled the accommodation space tectonically created during the Quaternary [9,10].

The Quaternary infill of the coastal sectors of the plain is not laterally isotropic and homogeneous because of the presence of layers of clastic sediments with different degrees of compaction. Dunal and beach sands, back-ridge (lagoonal and palustrine) silty clays, paleosols and thick peaty layers are the

main facies of this sedimentary prism. The back-ridge depressions hosted palustrine and marshy environments that were artificially drained in the last centuries.

2. Large-scale Geological Setting and Morpho-Evolution

The Volturno River plain is hosted in a graben-like structure (Figure 1), bordered by high-angle faults with offsets of thousands of meters that run at the foot of carbonate slopes [3,9,11,12]. The absence of Pliocene marine deposits in the deepest boreholes [13] suggests that the plain was above sea level during the late Tertiary [14]. During the Quaternary, the tectonic subsidence favored the accommodation of more than 3000 m of both sedimentary deposits and volcanic products [7,9,10]. During the first part of the Late Pleistocene, in fact, the filling of the plain was helped by the onset of volcanic activity from different sources. At about 40 ky, the huge CI eruption occurred [15] and uniformly covered the entire plain with a tens of meters-thick pyroclastic flow deposit.

In the upper part of the Late Pleistocene, the whole plain emerged due to the subsidence rate reduction and the contemporary last glacial regression. During the Holocene, the plain underwent diffuse flooding in concomitance with the peak of the post-glacial transgression. The subsequent decrease of the sea level rise favored coastal progradation and development of lagoon and swamp systems several kilometers inland from the present coastline [2–5].

3. Previous Works

The first detailed study of the upper Quaternary (upper Pleistocene-Holocene) sedimentary infill of the Volturno plain, based on both outcrops and boreholes, was provided by Romano et al. [1]. Six stratigraphic units from the lowermost marine sediments (Cancello terrace at 126 ky, marine stage 5.5) to the upper (beach dune and lagoonal/swamp sediments, Holocene in age) have been set up. The first-stage geomorphological reconstruction depicts a wide paleo-gulf bordered by calcareous mountains of the Apennine chain during early Late Pleistocene; after the “pre-CI” pyroclastic and volcanoclastic deposition, the paleo-gulf was substantially restricted to the central and the northern sectors of the plain (50–39 ky), due to differential uplift from the south (more) to the north (less) of the plain. In the second half of Late Pleistocene, the complete emersion of the plain was induced by glacio-eustatic sea-level lowering and enhanced by huge pyroclastic aggradation from CI eruption and by tectonic uplift of the north and eastern edges of the plain, at least until historical times. During the early Holocene, the rising of the sea level produced the progressive retrogradation of the plain, accelerated by the deposition of younger Phlegrean pyroclastic eruptions (12–23 ky). Deltaic and lagoonal environments characterized the lower plain until 5000 years ago, after substituting for swamp and marsh deposition during the Late Holocene progradation. This latter was induced by slowing down of the sea-level rise.

Barra et al. [2] further detailed the Holocene evolution of the southern sector of the Volturno coastal plain by new three boreholes. The beach-ridges and back barrier deposits lie on subaerial erosional surface superimposed on CI tuff. The ^{14}C dating on back barrier deposits suggested a 1 mm/year sedimentation rate during the last sea level rise until 6 ky BP (before present). The sedimentation rate increased up to more than 3 mm/year until 5000 years ago (the authors considered such a rate valid also for more recent times). The maximum ingress of marine layers in the area to the south of Regi Lagni is 1.5 km from the present-day coastal position. Chronological data showed that at least 5000 years, the progradation of the coastal ridges had not yet started to grow. The reconstruction of sea-level changes displayed no appreciable subsidence occurring in that area during Late Holocene.

On the basis of field and borehole data, Putignano et al. [3] focused on the Late Quaternary evolution of the north-eastern margin of the Volturno plain, confirming the stratigraphic subdivision by Romano et al. [1], stressing the reactivation of the main NO-SE and E-W border faults. Displacement of about 50 m toward the southwest of the MIS5 marine deposits and the pre-CI pyroclastic unit, in fact, indicates a Late Pleistocene activity of the Apennine-orientated fault (CI would appear to seal this

movement). The offset of about 10 m of the CI top along an E-W-directed fault shows a more recent faulting episode in the very Late Pleistocene-Holocene time span.

Santangelo et al. [4] individuated two distinct levels of lagoonal sediments in an 80 m-thick core drilled 28 km away from the present-day coastline. Such levels, buried at −40 m and −18 m, were dated at MIS7 (>160 ky) and MIS5 (105–130 ky), respectively. The sedimentation appears to be controlled by glacio-eustatism and tectonic subsidence. Between these deposits, a continental stage including the emplacement of pyroclastic products (140–160 ky Taurano Tuff) was clearly identified, as well as the continental stage between the second marine event and the CI unit, marked by a volcanoclastic unit (39–105 ky; Durazzano Ignimbrite [1,3]). The authors suggested a different tectonic history of the plain, not substantially stable, but with increasing subsidence mainly after the volcanic events.

Amorosi et al. [5] furnished a reconstruction of the CI top with a terraced and incised paleo-morphology created during the last sea-level falling. Moreover, the author identified upper Pleistocene, laterally discontinuous, alluvial bodies (14C-dated at 37 ky BP) between the CI and the post-CI volcanoclastic units. After the CI, a deepening-shallowing upward stratigraphic sequence reflects the backstepping of the wave-dominated delta system (latest Pleistocene-early Holocene, from 14C dating of lagoonal deposits at 8–12 ky BP), followed by the fore-stepping of pro-delta/strand-plain/alluvial facies, which was induced by deceleration of the last sea-level rise (post 5 ky). Modern alluvial and coastal plain deposits closed this sequence. The maximum ingressions (about 7 ky BP) of the shoreline was about 6 km NE of its present position.

A detailed study of the Lake Patria coastal lagoon, remnant of a larger lagoonal-marsh area developed in the southern part of the Volturno delta system, was carried out by Sacchi et al. [6]. Sedimentological and stratigraphic analyses of 12 cores allowed the dating of the inception of the back-barrier area around 4500–4800 years ago, caused by decreasing sea-level rise. About 3000 years ago, the lagoonal area reached its maximum extension keeping, connection to the open sea; after that, a fresh water input was established in the brackish lagoon. From Roman times, a vast marsh area was present until the Bourbons' reclamation that gradually reduced Lake Patria to its present size by constructing the Regi Lagni channel through the diversion of the Clanio River directly into the sea.

Santangelo et al. [7] illustrated the Quaternary geomorphological evolution of the Volturno plain, furnishing a review of all data previously published. They focus on the tectonic and glacio-eustatic controls influencing the coastline variations. According to the authors, a significant subsidence occurred in the Middle-Late Pleistocene, but with different rates along the plain. Tectonic subsidence was more homogeneous in the last 130 ky, with increasing trends mainly after the volcanic events. 40 ky-old CI eruption was responsible for the strong and rapid aggradation of the plain, which totally emerged and was therefore affected by fluvial erosion.

A land-sea profile, interpreted in terms of sequence stratigraphy and based on an extended set of on-land core data and offshore seismic reflection profile, has been carried out by Ruberti et al. [16] with particular reference to the Late Quaternary. In the same year, Matano et al. [17] illustrated the subsidence trends of the plain in the 1992–2010 interval, as inferred by SAR interferometry data. Significant subsidence (up to −420 mm) along the channel of the Volturno River and in its river mouth area occurs. Low subsidence or stability is recorded along the dune ridges as well as in a 10 km-large strip across the Volturno River. According to the authors, such a scenario appears linked to the lithological nature of subsurface deposits.

Finally, the offshore deposits of the last glacio-eustatic cycle in front of the plain have been investigated by Iorio et al. and Misuraca et al. [18–20]. Seismic profiles and cores allowed detailing of the depositional sequence located in the outer shelf off the Volturno plain. The oldest pro-grading units emplaced during the sea-level fall (−120 m) are limited at the upper boundary by a ravinement surface (regional unconformity) on which the youngest units developed [18,19]. The 3D modelling of the LGM (Last Glacial Maximum) erosional surface revealed a topographic high bounded by two opposite-facing sets of normal faults 11.5 km offshore of the Volturno River mouth [20].

4. Materials and Methods

In order to reconstruct the paleo-morphology of the buried roof of the Campania Ignimbrite, to determine the paleoenvironmental conditions of the area coinciding with the present-day Volturno plain, and to provide the stratigraphic synthesis of the Quaternary succession, a large amount of stratigraphic data has been acquired by the analysis of a collection of borehole logs from previous works and public institutions, such as the technical offices of municipalities and ISPRA (Italian Agency for Environmental Research and Protection). The subsurface lithostratigraphic dataset is based on 680 wells drilled in the plain and integrated by geological cartography and field survey. Sedimentological analysis and facies interpretation were acquired from the literature [1–5], whereas other unpublished stratigraphic logs furnished less detailed lithological data. Stratigraphic observations have been performed directly in the field where Quaternary sediments crop out. Age determinations for stratigraphic correlations are based on chronological constraints of volcanic and marine deposits (see references in Results).

All these datasets permitted the reconstruction of the Quaternary stratigraphic succession and its representation in a synoptic scheme (cf. Section 5.1). Such a task required an effort to homogenize data from different sources by using log charts and their precise positioning in a GIS. Subsurface and field data have been used to construct many geological cross-sections constituting an orthogonal grid (with a set parallel to the coastline). Vertical exaggeration of cross-sections is about 30x, due to the need of restitution of some stratigraphic details. In such a way, units' geometry and their stratigraphic relationships are better identified and readable. Of course, this involved an increase in apparent inclination of geological bodies and slopes.

In order to obtain useful elements to define the Late Quaternary evolution of the area as well as the tectonic relationships between Mount Massico and the surrounding plains, a geomorphological and structural survey were carried out to better define the elements of the recent brittle deformation (i.e., faults).

Finally, a contour map of the CI upper boundary has been drafted by GIS interpolation techniques.

5. Results

5.1. Stratigraphic Synopsis of the Late Quaternary Succession from the Volturno Plain

The stratigraphic analysis of the wells has allowed us to individuate 7 lithostratigraphic units based on homogeneous sedimentological and paleontological criteria. Table 1 summarizes the main lithological characteristics for each unit, including their stratigraphic contacts with the over- and underlying units. Numbering follows from the younger to the older deposits. For each unit, environmental interpretation is also provided. Stratigraphic positions and radiometric constraints enable us to propose a viable chronology, attributing an age interval for each unit.

Table 1. Summarized description of the main lithostratigraphic units recognized by core data and environmental interpretation (ages from literature).

Unit	Description	References	Chronology (Age BP)	Depositional Environment
U1p	Grey silty clays and silt with local sandy intercalations. Small mollusc shells (euryhaline fauna) are common. Thickness range: few metres—6 m. Transitional boundary with U1d. This unit is only located to coastal sector.	[5]	Holocene (0–12 ky)	Pro-delta
U1d	Well sorted, medium to coarse grey or yellowish sands, with abundant marine shells fragments, plant and rare pumice fragments. A general coarsening-upward trend occurs. Thickness range: few meters–16 m. Basal erosional contact with U2 and U4. Transitional boundaries with U1m landward and U1p seaward.		Holocene (0–12 ky)	Shoreface-beach-dune-ridge complex

Table 1. Cont.

Unit	Description	References	Chronology (Age BP)	Depositional Environment
U1m	Grey to dark grey clays with abundant organic matter and freshwater gastropods. Peat intercalations and sandy layers with mollusc and pumice fragments occur at places (Radiometric age from lower part of swamp/lagoonal deposits: 8–12 ky). Thickness range: few meters—30 m. Lower erosive boundary with U2, U3 and U4. Transitional boundaries with U1a landward and U1d seaward.	[5]	Holocene (0–12 ky)	Back-dune ridge complex Lagoon/estuary, coastal plain/swamp
U1a	Rooted and pedogenized, brown to grey clays and silty clays with abundant whitish pumices and plant fragments. Gravel with sand lens locally occurs. Thickness range: few meters—35 m. Lower erosive boundary with U2 and U3 and transitional contact with U1m seaward.		Holocene (0–12 ky)	Alluvial plain
U2	Two distinct events form this unit: Giugliano Ignimbrite (GI) and Neapolitan Yellow Tuff (NYT). The GI is pyroclastic flow deposit (23–18 ky), separated by paleo-sols from Campania Ignimbrite (CI) below and the incoherent NYT fall deposits above. The NYT consists of alternations of pumice and ash beds (Pozzolana), zeolitized yellow tuff, volcanic sands, cinerite deposits, sometimes reworked by fluvial erosion. Thickness range: few meters—30 m. Basal erosional contact with U3 and U4 and upper erosive boundary with U1.	[15,21]	Late Pleist. Holocene (12–23 ky)	Continental (volcaniclastics)
U3	Gravels and sands deposited as lens-shape bodies and characterized by upward transition to silty clays or silts with local peat intercalations (radiometric age 37 ky BP). White pumices and lapilli as well as pedogenized horizons locally occur. Thickness range: few metres—20 m. Lower erosional contact with U4 and U5; cover is represented by U1 and U2.	[5]	Late Pleist. (23?–37 ky)	Alluvial plain
U4	CI is a laterally continuous body formed by a pyroclastic flow, consisting of coherent (breccia Piperno) to totally incoherent (Cinerazzo) reddish or grey tuffs, with sandy scoriae, pumices and lithic elements. Thickness range: few metres—40 m. CI rests on coastal marine (U5) seaward and on the pre-CI volcaniclastic (U6) unit landward. The U1 and U2 units cover it by erosional contact.	[22]	Late Pleist. (about 40 ky)	Continental (volcaniclastic)
U5	Yellowish and grey sands with mollusc shells, clays with local peat lens. Intercalations of gravels, pyroclastic and travertine deposits also occur. Thickness range: 20 to >50 m. Upper (U4 and U3) and lower (U6) erosional contacts are present.		Late Pleist. (40?–50 ky)	Coastal-marine, transitional with continental episodes
U6	Pre-CI pyroclastic deposits produced by different eruptions from Roccamonfina (youngest events) and Phlegraean Fields (oldest events), locally separated by thin paleo-sols. Tuffs, pozzolana, lapilli and cinerite; rare lavas and clay lens. Thickness range: 5 to >60 m. The U6 rests on U7 by erosional contact and is covered by the U4 and U5. Radiometric age at the base 105 ka.	[4]	Late Pleist. (50–105 ky)	Continental (volcaniclastic)
U7	Fossiliferous clays and silts interbedded with yellow sands or fine gravels (Radiometric age 126 ky). Thickness range: 30 to >50 m. The U7 could be in contact at the base with the carbonate substrate and it is covered by the U6.	[1]	Late Pleist. (105–130 ky)	Coastal-marine, transitional

Unit 1—Holocene deposits (0–12 ky). This unit represents a complex and articulated sedimentary body formed by four sub-units: pro-delta (U1p), beach-dune ridge (U1d), lagoonal-swamp (U1m) and alluvial (U1a) deposits. The U1 bottom is normally the U4 pyroclastic unit (CI) which also represent its lateral contact towards north and east. The Pleistocene alluvial (U3) and pyroclastic (U2)

deposits represent a very discontinuous substrate for this unit, which rests on these only in some areas. By integrating subsurface and literature [1,2,5,6] data, the U1 can be considered as the Holocene depositional system having a complex transgressive-regressive architecture. It is articulated by a laterally adjacent facies belt, parallel to the coast, that progressively moving inshore shows: pro-delta, beach-dune ridge and back barrier (U1p, U1d and U1m) depositional units, until arriving at the more internal alluvial plain (U1a).

Unit 2—Pyroclastic flow and fall deposits (12–23 ky). This volcanoclastic unit is composed of the Giugliano Ignimbrite (GI, age 18–23 ky [15,21]) below, and the Neapolitan Yellow Tuff (NYT, ~12 ky in age [21]) above, both deposited in subaerial conditions. The U2 mostly occurs in the southern sector of the Volturno plain (Giugliano, Qualiano, Melito di Napoli, Casavatore, Lake Patria) and shows a lower erosive contact with the U4 (CI) marked by a paleosol and, where it does not crop out, is covered by the U1 unit. The U2 is rarely documented on the right side of the Volturno River and has been mostly removed by fluvial erosion [12].

Unit 3—Pleistocene alluvial plain deposits (23?–37 ky). This highly discontinuous and subsurface unit is represented by channeled fills of paleo-valleys incised in the U4 or fluvial terraces created by pyroclastic material reworking of the underlying U4 unit. Amorosi et al. [5] dated this unit at about 37 ky BP. In places, the incision of the paleo-river appears to cross the entire U4, reaching the underlying coastal-marine unit (U5), as testified by erosive contacts of some alluvial lens directly with the U5, described below.

Unit 4—Campanian Ignimbrite (CI, about 40 ky). This unit is attributed to the highly explosive eruption of the CI, which entirely covered the Campania Plain at ~40 ky [22]. It borders the southern and western flanks of the Massico and Caserta Mountains, respectively, and represents a laterally continuous horizon with an articulate paleo-topography clearly traced in the subsurface. CI upper boundary appears at a progressively higher depth (35/40 m b.s.l.) in the central sector of the Volturno Plain [1,4,5].

Unit 5—Coastal-marine and transitional deposits with alluvial episodes (40?–50 ky). This subsurface unit is often the substrate of the Unit 4 at depths more than 40 m b.s.l. The upper limit is very irregular and is placed between 20 and 10 m a.s.l. in the Mondragone and Sparanise area, but between 10 and 40 m b.s.l. moving from the coastal towards the inner sector of the plain. Based on lithological characteristics and stratigraphic position, a correspondence with the unit 4 of Romano et al. [1] can be established.

Unit 6—pre-Campanian Ignimbrite volcanoclastic deposits (50–105 ky). This subsurface unit appears more discontinuous in the northern (top depth between 10 m b.s.l. and 30 m a.s.l.) than in central and southern (20/60 m b.s.l. top depth) sectors of the plain. U6 is situated stratigraphically under the U5 in the southern sector but directly under the U4 in the Villa Literno—Casal di Principe area. U6 is also horizontally adjacent to U5 under the Regi Lagni area suggesting possible dislocations of these units. Some correspondence with the Unit IV [4] and Unit 5 [1] is based on chronostratigraphic (~50–105 ky) and paleo-environmental constraints.

Unit 7—Coastal-marine and transitional deposits (105–130 ky). This subsurface unit appears to be continuous and the deepest, the upper boundary ranging between 40 and 70 m b.s.l. and, between 0 and 30 m b.s.l., on the left and right sides of the Volturno River, respectively. This differential depths could suggest a tectonic dislocation. The minimum thickness estimated is about 50 m even if the base of this unit has never been reached in the studied boreholes. These deposits cover lava bodies in the southern sector of the plain ascribed to the buried Parete volcano [23]. U7 corresponds to marine sediments of unit 6 from Romano et al. [1] (U/Th dating on *Cladocora*, about 126 ky) and unit III from [4] (age > 105 ky).

5.2. Geological Cross Sections

Mapping and correlation of outcrop and subsurface stratigraphic data in relation to the present sea level allowed us to outline the presence/absence, elevation, thickness and stratigraphic relationships

of the seven stratigraphic units above illustrated. Six geological sections have been constructed (Figure 2); three of them are parallel to the major river axis, starting from the coast to the inland (A–A', B–B' and C–C' from the north to the south, Figure 3), whereas other three are orthogonal to the first ones (i.e., NW–SE oriented) and labelled D–D', E–E' and F–F' (Figure 4). All these sections show the late Pleistocene–Holocene succession of the marine-to-continental infill, resulting from interactions among tectonics, eustatic changes, and sediment supply variations, in turn largely affected by neo-tectonic faults.

The A–A' section shows, in its deepest portion near the north-east boundary of the plain, the coastal-marine and transitional deposits (U7) covered by the pre-CI continental volcanoclastic unit (U6). These two units are attributed respectively to 105–130 ky and 50–105 ky ages [4]. Further, in this section the U7 directly rests on the Mesozoic carbonate bedrock and the CI (U4) directly covers the U6. The staircase trajectory of their upper boundaries buried at the base of the carbonate slope shows the downthrown structure of the north-eastern border of the plain, due to normal faulting (A–A' section, Figure 3).

U4 crops out along the border ridges of the plain, showing thickness up to 50 m in different points. It corresponds to the volcanic products of the 40 ky-old major eruption of CI, forming a laterally continuous body cropping out along the carbonate slopes of border mountains and drilled by many cores in the plain. The geological sections illustrate a very irregular profile shaped by erosion due to the long subaerial exposure and articulated by exposed and buried faults. An erosive boundary (mountainward) and U5 coastal-marine and transitional deposits (seaward) clearly separate in subsurface this volcanic unit from the pyroclastic/volcanoclastic lower unit (U6) in the A–A', C–C', and D–D' sections (Figure 3). Moreover, the U5 upper limit is progressively dislocated by faults at greater depths toward the central part of the plain, as one can observe in the D–D' and F–F' sections (Figure 4). It follows that a couple of major faults are parallel to the southern slope of Mt. Massico (i.e., NE–SW-directed), the carbonate ridge that closes the plains toward NW. An antithetic fault is placed in the central-southern sector of the plain, to the south of Volturno River, constrained by a lot of boreholes used for the construction of D–D', E–E' and F–F' sections (Figure 4).

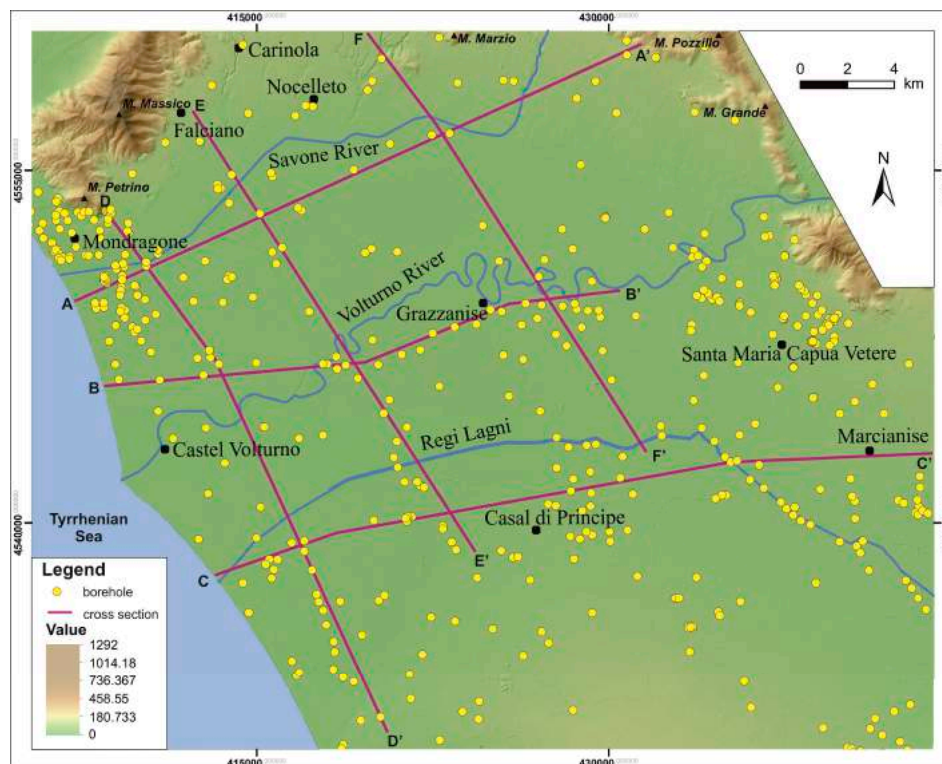


Figure 2. Locations of boreholes and geological cross-sections.

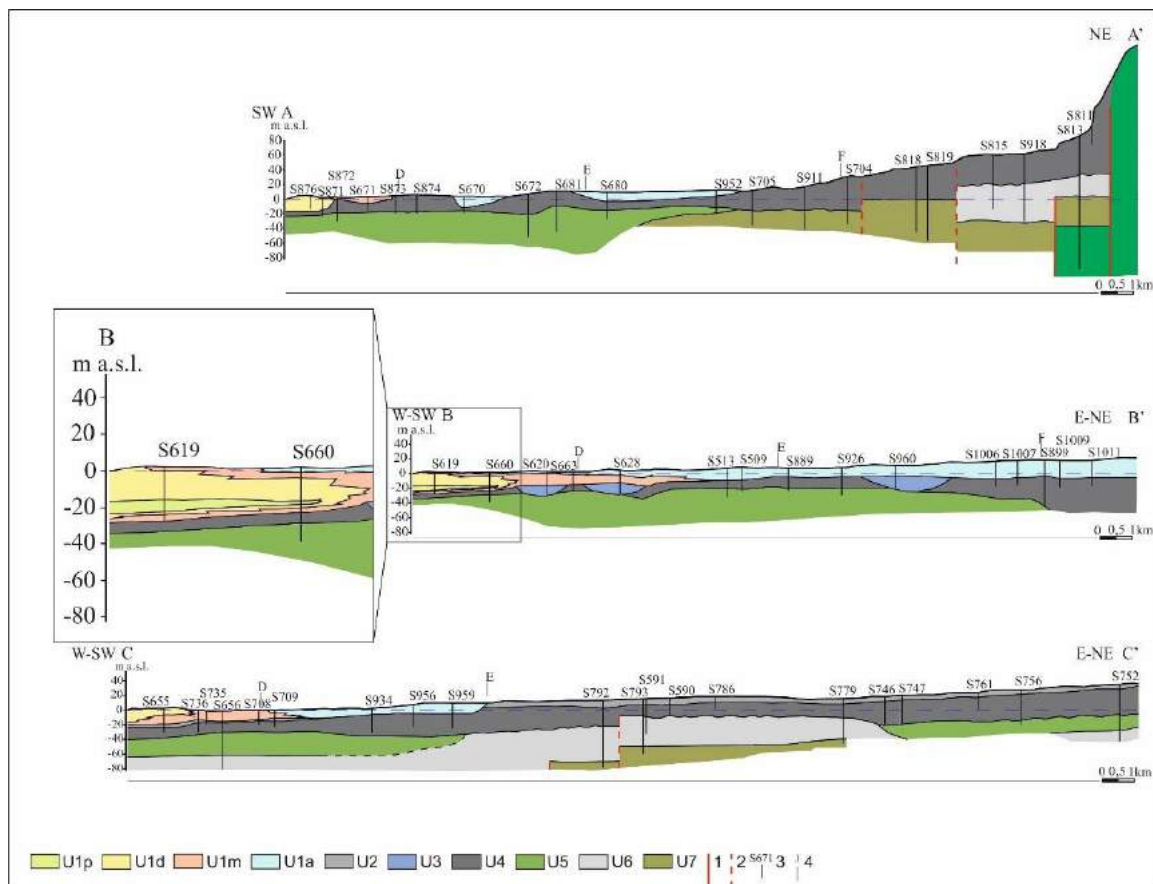


Figure 3. A–A’, B–B’, and C–C’ geological cross-sections. U1p: pro-delta deposits; U1d: beach-dune ridge deposits; U1m: lagoonal-swamp deposits; U1a alluvial deposits; U2: pyroclastic flow and fall deposits (12–23 ky); U3: Pleistocene alluvial deposits (23?–37 ky); U4: Campanian Ignimbrite deposits (CI, about 40 ky); U5: coastal-marine and transitional deposits with alluvial deposits (40?–50 ky); U6: pre-Campanian Ignimbrite volcanoclastic deposits (50–105 ky); U7: coastal-marine and transitional deposits (105–130 ky); 1: fault; 2: uncertain fault; 3: borehole; 4: interception with cross sections.

The U4 thickness wears thinner in the plain where the fluvial erosion has been active until now, so that the maximum thickness of the overhead Holocene alluvial deposits (U1a, about 40 m) is in correspondence with the minimum of the U4 (about 10 m in the E–E’ section and 15 m in the F–F’ section, Figure 4). Where the past fluvial incision reached the underlying coastal-marine U5, upper Pleistocene alluvial deposits belonging to the U3 are preserved (see B–B’ and E–E’ sections, Figures 3 and 4); their lens-shaped geometry depicts the paleo-channels fillings. The fluvial erosion appears partly sets up along a tectonic lineament: buried channelled fill lies to the north of the *Regi Lagni*, where the antithetic fault above mentioned is tentatively traced (see E–E’ section, Figure 4).

The post-IC volcanic unit U2, originally covering the entire plain, was mostly removed by fluvial processes and occurs only south of Volturno River. It crops out as a quasi-continuous and thin level at the north of the Phlegraean Fields and mainly on morphological highs in the southern portion of the plain [5]. This horizon runs into subsurface reaching the coast at the south of the *Regi Lagni* (C–C’ section, Figure 3). This unit (12–23 ky BP, [15,24]) produced a shoreline progradation due to both volcanoclastic aggradation and volcano-tectonics [2] in spite of sea level rise starting after the Last Glacial Maximum.

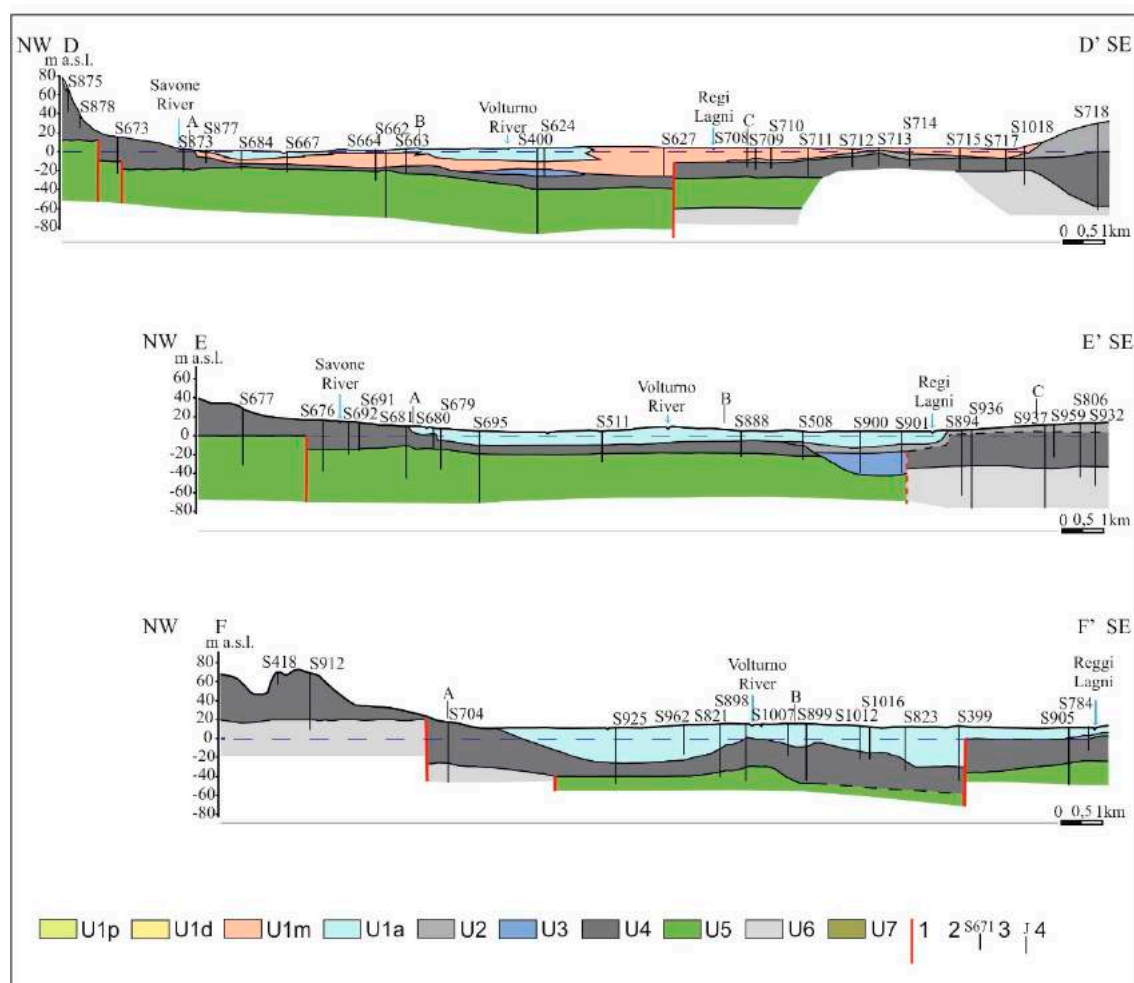


Figure 4. D–D', E–E', and F–F' geological cross sections. U1p: pro-delta deposits; U1d: beach-dune ridge deposits; U1m: lagoonal-swamp deposits; U1a alluvial deposits; U2: pyroclastic flow and fall deposits (12–23 ky); U3: Pleistocene alluvial deposits (23?–37 ky); U4: Campanian Ignimbrite deposits (CI, about 40 ky); U5: coastal-marine and transitional deposits with alluvial deposits (40?–50 ky); U6: pre-Campanian Ignimbrite volcanoclastic deposits (50–105 ky); U7: coastal-marine and transitional deposits (105–130 ky); 1: fault; 2: uncertain fault; 3: borehole; 4: interception with cross sections.

The youngest unit (U1) mostly represents a sedimentary coastal wedge, Holocene in age, split into U1p, U1d and U1m equivalent to pro-delta, beach-dune, back-dune systems, respectively; the above mentioned U1a covers the inner sectors of the plain. The U1 rests on the U2, U3 and U4 units, separated by an erosional surface. The coastal wedge has retro-gradational facies architecture in the lower portion of the U1, clearly illustrated in the B–B' and C–C' sections (Figure 3). The Holocene sea-level rise may account for this facies arrangement [5]. A variable landward shifting of the marine-coastal wedge can be traced by the borehole data plotted along the orthogonal sections to the coast. The beach-dune system (U1d), up to 25 m thick, migrates landward from a minimum of about 1.5 km immediately south of Mondragone (A–A' section) to a maximum of 3.5 km in the Castel Volturno area (B–B' section). Only in this coastal sector are the pro-delta deposits (U1p), a few meters thick, individuated in the cores, above the transgressive barrier sands. The back-dune system (U1m) including lagoonal-estuarine, swamp and coastal plain environments, appears to reach the maximum landward position, about 9 km along the Volturmo axis, but up to about 3 and 6 km at the north and south of the Volturmo River, respectively. The maximum thickness of the U1m occurs in the coastal sector enclosed between the Volturmo and *Reggi Lagni* channels (see D–D' section, Figure 4). Here, these deposits appear to suture the antithetic north-dipping fault roughly parallel to the counter-Apennine Mt. Massico fault system.

Upwards, the U1 facies shows a coastal prograding pattern produced after the maximum flooding surface aged about 7 ky [5]. The seaward shift of U1m and U1a, as well as of the sand beach-dune ridge and delta systems up to where they reach the present coast configuration, is delineated by the core stratigraphic succession more or less aligned to the depocenter (B–B' section, Figure 3). The most recent stage leads to a progressive continental aggradation, with the swamp and marshy areas disappearance in the last 2 ky [5,6].

The Late Quaternary Volturno valley infill architecture, above delineated, allowed us to create a more complete scheme of the main stratigraphic relationships among the seven units recognized in this work (Figure 5).

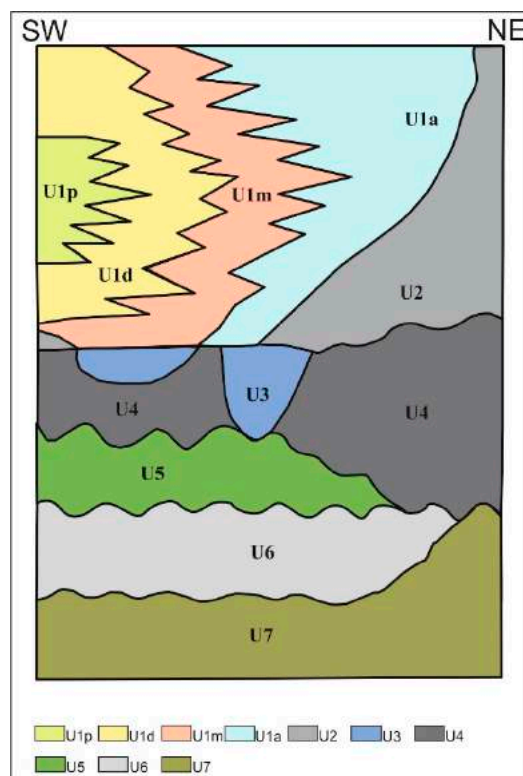


Figure 5. Scheme of stratigraphic relationships between the seven lithostratigraphic units of the study area. U1p: pro-delta deposits; U1d: beach-dune ridge deposits; U1m: lagoonal-swamp deposits; U1a alluvial deposits; U2: pyroclastic flow and fall deposits (12–23 ky); U3: Pleistocene alluvial deposits (23?–37 ky); U4: Campanian Ignimbrite deposits (CI, 40 ky); U5: coastal-marine and transitional deposits with alluvial deposits (40?–50 ky); U6: pre-Campanian Ignimbrite volcanoclastic deposits (50–105 ky); U7: coastal-marine and transitional deposits (105–130 ky). SW: south-west; NE: nord-est.

5.3. Tectonics

The genesis of the graben-like structure that hosts the present-day Volturno coastal plain and its tectonic evolution (including tectonic subsidence of the plain) can be traced back to polyphasic brittle deformation, exerted by a system of faults mainly constituted by two orthogonal sets (Figure 6). The most ancient deformational stage, which occurred between the Pliocene and early Pleistocene, created the embryonal low with a half-graben geometry, like other structural depressions of the Tyrrhenian side of the Apennines orogenic chain [11], and set the conditions for their evolution and acquisition of accommodation space for marine sediments. At the passage between the Early and the Middle Pleistocene, the extension direction switched from NW-SE to NE-SW, causing the formation or re-activation of Apennine-directed and/or E-W-oriented high-angle faults as normal faults (Figure 6). The same extensional axis characterizes the late Pleistocene-Holocene and present-day stress field, accompanied by relevant volcanic activity.

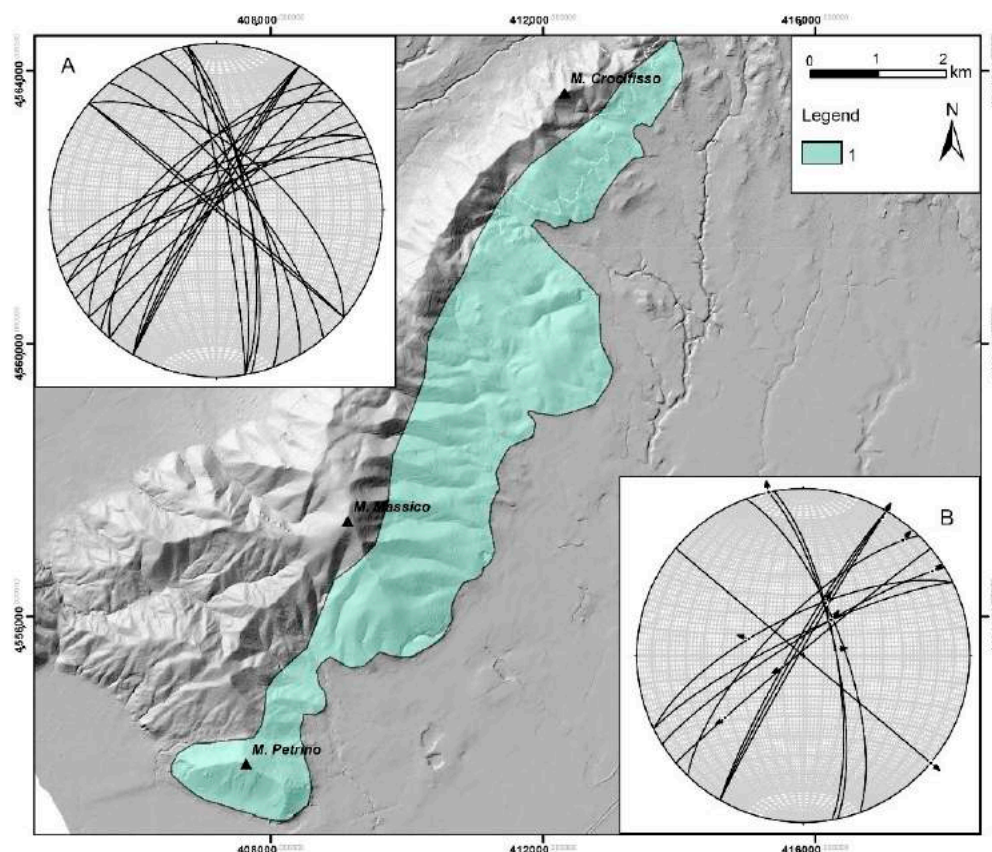


Figure 6. Measurement stations (box 1 in the legend) and related stereoplots of brittle structures from the southern slope of Mt. Massico. (A): stereoplot of faults; (B): stereoplot of faults with kinematics.

Geophysical data and stratigraphic constraints from deep boreholes suggest that the Apennine-trending faults dip towards the south-west and are the most superficial evidence of a complex system of listric faults that gave rise to the asymmetrical extensional structures strongly controlling the general physiography of the region [11].

Two sets of faults with clues of recent activity have been identified in the study area (Figures 6 and 7). Both displaced the CI, so showing post-40 ky offsets. Late Quaternary tectonics is evidenced by the decametric vertical separations operated by these faults. The interval of possible slip rates, calculated on the basis of chronostratigraphic constraints and considering offsets from 10 to 30 m, is equal to 0.25–0.77 mm/year. Their average slip rate, that would represent the tectonic subsidence rate of the plain, is about 0.5 mm/year.

The structural analysis performed along the southern slope of Mt. Massico permitted us to identify different kinematic indicators on the fault planes. Orientation data from three measurement stations showed that NW-SE-striking faults are featured by normal, transcurrent, and transtensive markers. In this case, the strike-slip component is always left-lateral. Regarding the NE-SW-directed planes (i.e., counter-Apennine set), both right-lateral and left-lateral components of slip are present, whereas dip-slip indicators are absent. Therefore, the counter-Apennine faults surveyed at the north-western border morphostructure of the plain can be interpreted as second-stage (i.e., re-activated) transfer faults that accommodated the youngest extensional deformation with a NE-SW-trending tensile axis. Large-scale evidence (volcanism, hydrothermal phenomena, morphological anomalies, sinkhole alignments) suggest that the counter-Apennine lineaments are expression of very recent tectonic activity [1,25,26].

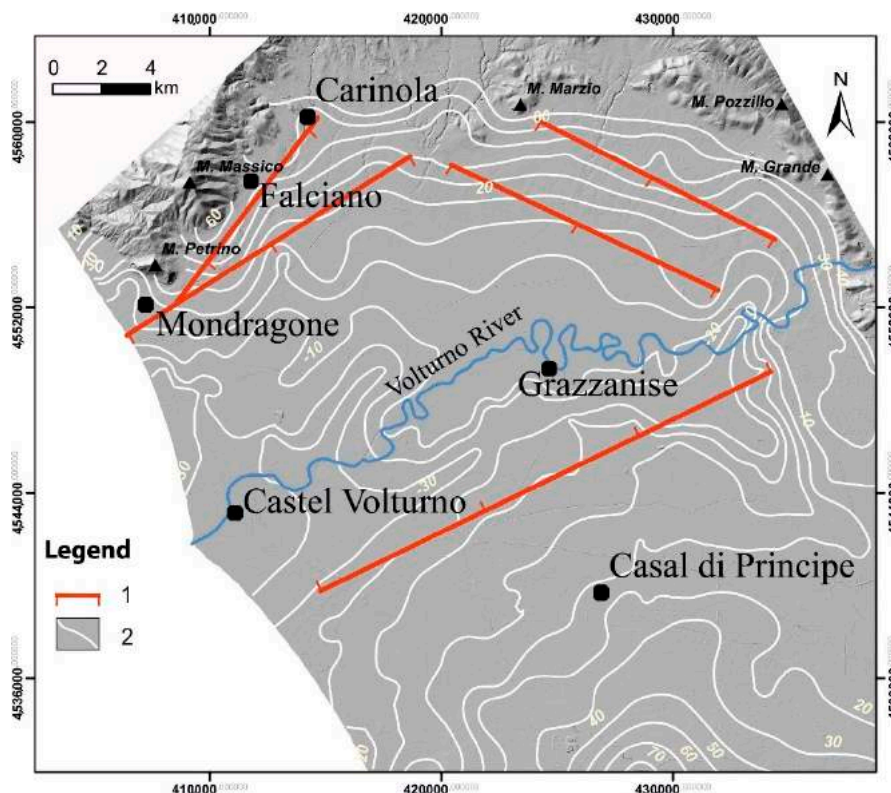


Figure 7. Map showing the CI unit upper morphological surface and the Quaternary main faults. Legend: (1) fault; (2) contour lines of the CI roof. In blue, the present Volturno River.

5.4. Geomorphology

Close to the present coastline, a composite sandy ridge testifies to the evolution of the Holocene barrier-lagoon system. It disappears inland under a flat, muddy, back-dune depression. These sandy ridges constitute the same dune system with a mean height of about 3 m a.s.l., interrupted by rivers and artificial drainage channels. The back-ridge depressions, spread over a large area of the plain with a mean height of about 0.50–1.5 m b.s.l., hosted palustrine and marshy environments, artificially drained in modern times.

At the base of the slopes there are alluvial fans and waste deposits, Late Quaternary in age. Carbonate slopes facing to the plain generally presents regularized profiles and rectilinear basal envelopes inherited by mechanisms of recession occurred under cold climate conditions. They are often dissected by minor streams—related to a warmer-humid later period—that in some cases have incised transversal valleys, then were partially filled by alluvial sediments.

On the basis of boreholes analysis, the trend of the CI roof was reconstructed. Such a paleomorphology shows an articulated buried surface, significantly eroded and sharply incised by streams. In particular, a paleovalley can be clearly recognized about two kilometres to the south of the present-day course of the Volturno River (Figure 7). Here, the paleoriver seems responsible for a fluvial incision of about 10 m, carved in the CI (the upper morphological surface of this unit is at -20 m at about 24 km from the coastline, whereas the same element is at -30 m at about 8 km from the present coast). This paleoriver can likely represent the ancient (i.e., post-CI and pre-Holocene) course of the same Volturno River.

6. Discussion and Conclusions

Geological and geomorphological data here presented allowed us to define a new and more detailed picture of the morphological, tectonic and sedimentary evolution of the Volturno River alluvial-coastal plain during the terminal part of the Quaternary (Figure 8).

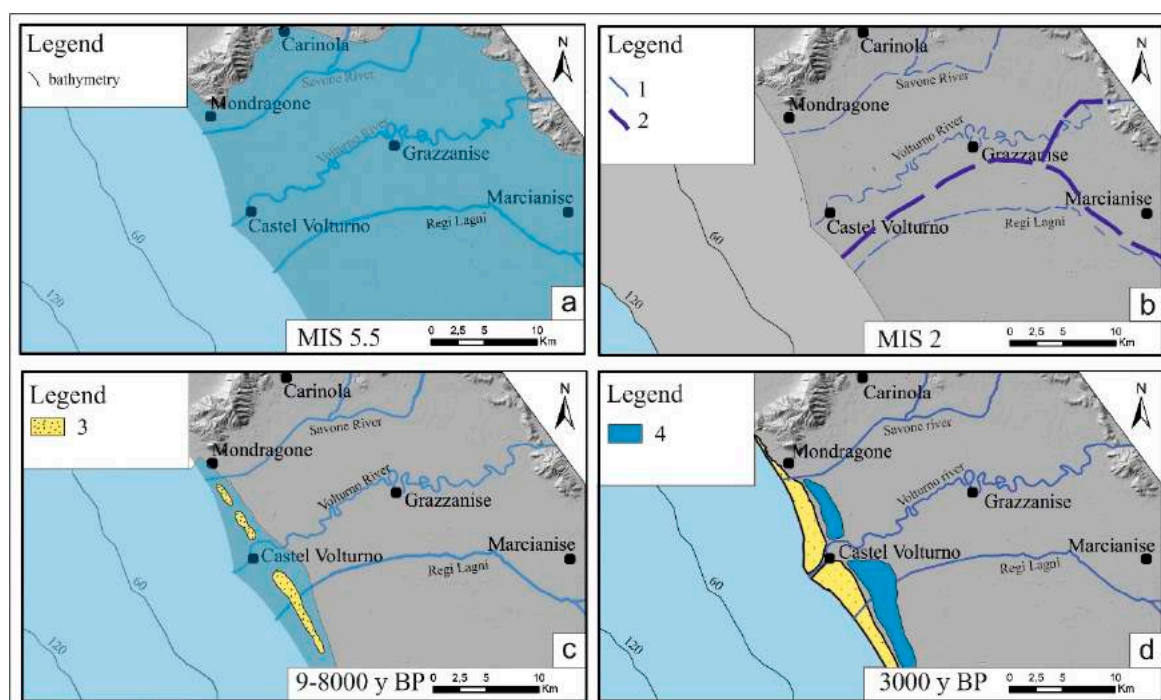


Figure 8. Morpho-evolutive stages (see text for explanation). Legends: (1) Current rivers; (2) Paleo-Volturno course; (3) dunal ridge; (4) swamp.

During the Tyrrhenian stage (MIS 5.5), a marine sedimentary environment (represented by deposits of U7) took place in the paleogulf previously generated and bordered to the north-west and north-east by faulted ridges mainly made of Mesozoic carbonates. A stage of pyroclastic aggradation (testified by U6 deposits), which perhaps occurred in the MIS 3, provoked a shift of the coastline towards the sea, especially in the southern part of the study area due to the greater thickness of such deposits observed in cross-sections C–C', D–D', E–E' and F–F' (Figures 3 and 4). Marine and transitional facies, with alluvial bodies, was deposited in this restricted paleogulf. They mirror a highstand phase, whose effect reaches the massive Mesozoic limestone of the Mt. Massico foothill (i.e., the sandy sedimentation today buried at the north-western edge of the current plain, see D–D' and E–E' cross-sections, Figure 4) around 50,000 years ago [1] (MIS 3.3). During this entire period (early Late Pleistocene), the permanence of the marine environment was undoubtedly favoured by subsidence, as testified by the share of beach rocks dated by Romano et al. [1] at 126 ± 11 ky BP, found at -50 m a.s.l., 56 m lower than the expected level (Figure 8a).

The scenario above described changed completely during the eustatic lowering of the final part of the Late Pleistocene (from MIS 3.1 to MIS 2), probably also coupled to the reduced subsidence. The eruption that caused the placement of the Campanian Ignimbrite (40 years BP [22]) occurred in a subaerial environment (Figure 8b). The resulting increase in height of the topographical surface in coincidence with a low eustatic level of the sea set the conditions for the triggering of a new stage of fluvial erosion that reshaped the morphology of the roof of this unit [1,12]. The U3 alluvial sediments were deposited in this stage near the Volturno River and south of it.

The subsurface trend of the CI roof shows that tectonics is still active in the final part of the Late Pleistocene, with the uplift of U4 in the boundary sectors of the plain. Two sets of faults, in fact, displaced the CI with decametric offsets (Figure 7). A paleovalley south of the current Volturno River axis – which migrated northward after the MIS2—is also well recognizable, as confirmed by the presence of buried upper Pleistocene alluvial deposits (U3) associated to this morphological feature. Such a northward migration may be attributed to the activity of the NE-SW-striking Mt. Massico fault system that would have generated a NW-directed tilt of the whole area.

Seismic data from the outer shelf in front of the Volturno River mouth [20] showed that a buried structure (i.e., a volcano older than 0.7 Ma) bordered by NE-SW oriented normal faults may have controlled the southward shifting of the sedimentary depocentres related to Holocene transgressive deposits. This would confirm the mobility processes (i.e., lateral migration) of the Volturno River detected in this study, indicating an “inversion” of sense of shift (southward to northward) during the Late Quaternary. It means that the major NE-SW-directed faults could have been alternatively activated (before the south-Volturno fault and then the Mt. Massico fault).

A new cycle of eruptions from the volcanic district of Phlegraean Fields and the consequent emplacement of the Giugliano Ignimbrite and the Neapolitan Yellow Tuff (U2) between 23 and 12 ky BP mainly interest the southern part of the study area, maybe suturing the southernmost counter-Appennine fault.

Finally, the Holocene marine transgression affecting the plain starting from about 10,000 years BP established a lagoon environment in the coastal belt (cf. U1m deposits), that probably lasted up to about 5000 years BP, as suggested by dating of lagoon deposits from the nearest Garigliano River plain [27]. The maximum ingression of the shoreline in the Volturno plain was about 3–4 km inland (Figure 8c). The successive seaward migration of the sandy shore induced the sedimentary filling of the lagoon areas and their replacement by marshy stretches of water (Figure 8d). During this last stage, the central area of the plain has retained substantial tectonic stability, as suggested by the geometry of Holocene sediments, which levelled the paleomorphology.

In conclusion, the significant achievements of this research are a greater knowledge of distribution and evolution of the coastal-marine to continental palaeoenvironments of the Volturno plain during the Late Quaternary, and the reconstruction of the roof of the Campanian Ignimbrite that allowed upgrading of the 3D shape of the Volturno plain paleomorphology before the deposition of late upper Pleistocene—Holocene sediments. It is now possible to infer an asymmetrical shape of the ancient morphology of the plain—with a steeper slope toward the north-west border (i.e., Mt. Massico morphostructural high)—and the lack of coincidence between the present course of the Volturno River and the main buried bedrock incision. Taking into account also the subsidence data from the Volturno plain [17,28], Late Quaternary tectonics should therefore be considered active and able to produce the asymmetry the CI roof as well as the lateral migration of the Volturno River.

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