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Soils in Understanding Land Surface Construction: An Example from Campania Plain, Southern Italy

Antonella Ermice [1,*], Rossana Marzaioli [1], Marco Vigliotti [2], Pierferdinando Lamberti [1] and Daniela Ruberti [2]

[1] Department of Environmental, Biological, Pharmaceutical Sciences and Technologies, University of Campania L. Vanvitelli, 81100 Caserta, Italy; rossana.marzaioli@unicampania.it (R.M.)
[2] Department of Engineering, University of Campania L. Vanvitelli, 81031 Aversa, Italy; marco.vigliotti@unicampania.it (M.V.); daniela.ruberti@unicampania.it (D.R.)
* Correspondence: antonella.ermice@unicampania.it

Abstract: The contribution of sediment transport and accumulation to soil formation was investigated in an area characterized by continental sedimentary activity since the Late Pleistocene. The area was the north-eastern portion of the large Quaternary graben represented by the Campania Plain, which is rimmed to the north–east–south by the Mesozoic carbonate Apennine nappes. The plain was filled mainly by products generated by eruptions from the Phlegrean Fields, which were also distributed on the slopes bordering the plain and remobilized toward the adjacent surfaces. Five sites were selected in the area in question. They were studied using morphological features and pertinent characteristics of the mineral soil fraction >2.0 mm, such as their volume and lithological description. Soils were compared to selected lithostratigraphic sequences characterizing the studied area, which were collected from literature and reinterpreted in pedological keys. The results showed that soils derived from the emplacement of Phlegrean primary volcanic materials, such as Campania Ignimbrite (~39–40 ky B.P.) and Neapolitan Yellow Tuff (~15 ky B.P.), with the related weathering products, and from volcanic materials reworked and transported by alluvial/colluvial episodes. The latter formed contrasting soil horizons which, differing in both rock fragment content and lithological composition, testified to the presence of lithological discontinuities. The formation of the horizons in question interrupted the genetic sequence derived from the in situ alteration of the volcanic substrata, suggesting that processes of transport and redistribution of sediments from the adjacent mountain slopes contributed to soil formation. The comparison of the pedostratigraphies with the lithostratigraphic sequences indicated a strong relation between geomorphic and pedogenetic events.

Keywords: volcanic soils; lithostratigraphy; soil lithological discontinuities; sedimentary activities; Campania Plain (Southern Italy); Late–Pleistocene–Recent

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1. Introduction

Pedogenesis implicates formation with the time of soil horizons with different characteristics and properties, depending on the processes active on the soil parent material. The participation of multiple materials in soil architecture can affect soil horizon differentiation, as occurs in the presence of repeated sedimentary processes [1]. Sedimentation is one of the geological processes responsible for land surface construction, and when involved in soil genesis, it is variously incorporated in most of the pedogenetic models developed for understanding the pedological systems and their complexity [1]. Intricate genetic relationships among soil portions can derive from the interplay of sedimentary processes in soil formation as an effect of the introduction of various parent materials differing in both particle size and lithological composition, which produces the so-called soil lithological discontinuities (LDs). The latter are contacts between horizons with significant changes in particle size distribution or mineralogy, which represent differences in lithology within a soil [2]. The detection and interpretation of the LDs are a crucial step in soil studies [1,3]

due to the great influence of the parent material on the soil genesis pathway. Lithologically contrasting horizons occur in a lot of soils in the world: Ahr et al. [3] report the wide occurrence of LDs on the planetary surfaces "in loess and sand covers over glacial tills in relict periglacial environments across Europe, in volcanic soils, in sandy Atlantic and Gulf Coastal Plain soils, in the loess-mantled landscapes in North America [4,5], in soil complexes in Australia, and in highly weathered soils of the tropics" [4,5].

The relationships among the contrasting horizons and layers are important for numerous investigations in earth and environmental sciences due to the implications of LDs in pedological, ecological, and geomorphological processes and their role as stratigraphic, archeological, and paleoclimatic markers [1,3–9]. LDs are useful for ascertaining the depositional history of a soil, which is relevant in reconstructing the relationships between soils and geomorphic surfaces. Pedological studies also benefit from the detection and interpretation of LDs because of the influence of vertical changes on all processes of translocation along a soil profile. From this perspective, the vertically differentiated zones along a soil profile are important in the investigations of landslide hazard and risk prediction due to the influence exercised by these soil portions on the soil hydraulic behavior [10–12].

Depositional processes, such as the fallout of tephra, as well as the transport of colluvial and alluvial materials, can impact the formation of the pedological covers through both allogenic sediment scattering and massive and instantaneous burial. In this last case, deposits blanket the surfaces faster than they can be incorporated into soils by pedogenetic processes [1,5]. In this way, geological deposits generate vertical breaks in the "regular" pedogenetic activity, generating contrasting horizons. The resulting complex soil patterns can be further complicated by lateral variations, especially on steep slopes that simultaneously operate as sinks and sources, and can receive and lose variable portions of sediments and soils, with consequent soil morphological and constitutional changes over short distances. An example, among others, is offered by the complex distribution of the pedological covers on the carbonate Campanian Apennines in Southern Italy, where the combination of geomorphological, sedimentological, and climatic circumstances produces the removal and transport of portions of pedogenized materials and/or the primary Phlegrean and Vesuvian pyroclastics deposited on such reliefs, interrupting the continuity of the sequences, truncating and burying the surfaces [13]. By contrast, in flat areas and in the absence of important tectonic movements, the geomorphological stability should enable the preservation of the pedostratigraphic sequences that document sedimentary inputs, stimulating the study of the role of sedimentation on soil formation.

Such a geomorphological setting is offered by the large structural depression corresponding to the Campania Plain in Southern Italy (Figure 1 [14,15]). The Campania Plain evolved during the Quaternary as a large graben [16] in which thousands of meters of sediments and volcanic deposits accumulated due to fluvial and coastal processes along with volcanism [17–24]. To the North, East, and South, the Plain is rimmed by the Mesozoic carbonate Apennine nappes, while its western portion faces the Tyrrhenian Sea and hosts the Phlegrean Fields and Somma–Vesuvius volcanic districts. The latter, developed during the Late Pleistocene, produced important volcaniclastic deposits that interfingered with alluvial and transitional sediments, covering the Apennine ridges. Such a morpho-sedimentary evolution is particularly developed in the north-eastern sector of the Plain, facing the foothills, where pyroclastic deposition was associated with weathering processes that affected the carbonate slopes, favoring the formation of alluvial fans and colluvial deposits often enriched in detrital carbonate components [16–25].

While extensive geological literature is available on the stratigraphic concerns, especially regarding surface processes (see the references in this manuscript, among others), less interest has been devoted to the mechanisms of formation and development of the pedological covers.

The aims of this work were to detect the soil cover organization and the main factors implicated in the pedogenesis in an area characterized by active sedimentary processes in the past and explore the genetic relationships existing among the soil horizons, as well as

the effects on pedogenesis of the sedimentary–geomorphic processes in the studied context. The study was conducted through field investigation and pertinent laboratory analyses of soil profiles surveyed in an area located in the north-eastern part of the Campania Plain and by comparing the soils to selected local lithostratigraphic sequences collected from the literature.

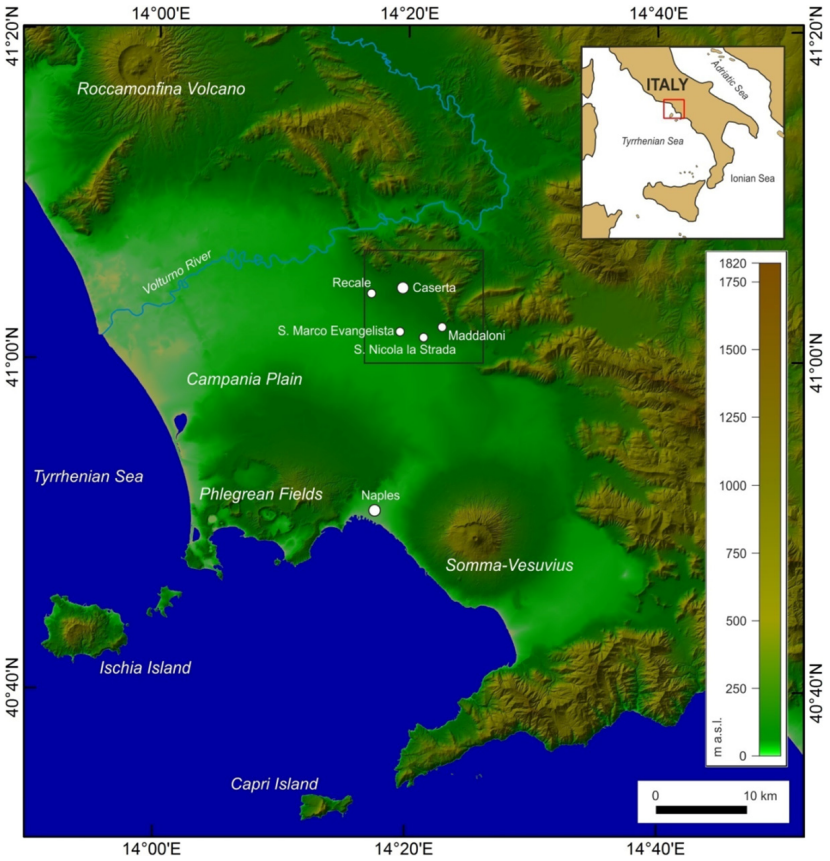

Figure 1. Location map of the study area (black box). Digital Terrain Model of the Campania Plain, based on TinItaly dataset [14,15].

2. Study Area

The study area corresponds to the north-eastern part of the Campania Plain, delimited by the towns of Caserta, Maddaloni, Recale, S. Nicola la Strada, and S. Marco Evangelista (Figure 2). The plain was filled with clastic and volcanic sediments deriving from the interaction between fluvial deposits from the Apennines Mountain and the sea and the numerous pyroclastic products emitted mainly by Phlegrean Fields. These latter are a group of polygenic volcanoes to the west of Naples, whose activity lasted between about 205 and 157 ky B.P. [26]. The deepest portion of the Campania Plain consists of marine, transitional, and continental deposits from the Middle–Late Pleistocene, which are sealed at the top by pyroclastic materials. One of the last explosive eruptions of the Phlegrean Fields emplaced Campania Ignimbrite (CI) (~39–40 ky) [27,28], a thick (50 m on average), laterally continuous, pyroclastic unit that covered the whole Campania Plain. In the studied sector of the Plain, this unit represents one of the two most important marker levels recognized in the subsoil, overlain by the surge deposits of the following eruption known as the Neapolitan Yellow Tuff (NYT) (~15 ky B.P.) [29,30]. A volcanic ash layer from the Y-3 eruption, dated 29,000 years B.P., could have affected sedimentation in the area in question [31].

Colluvial layers form a large piedmont *glacis*, which is laterally associated with the hills and characterized by wedges of detrital fans consisting of reworked volcanoclastic and calcareous debris [17]. Alluvial sediments also occur close to the hill slopes.

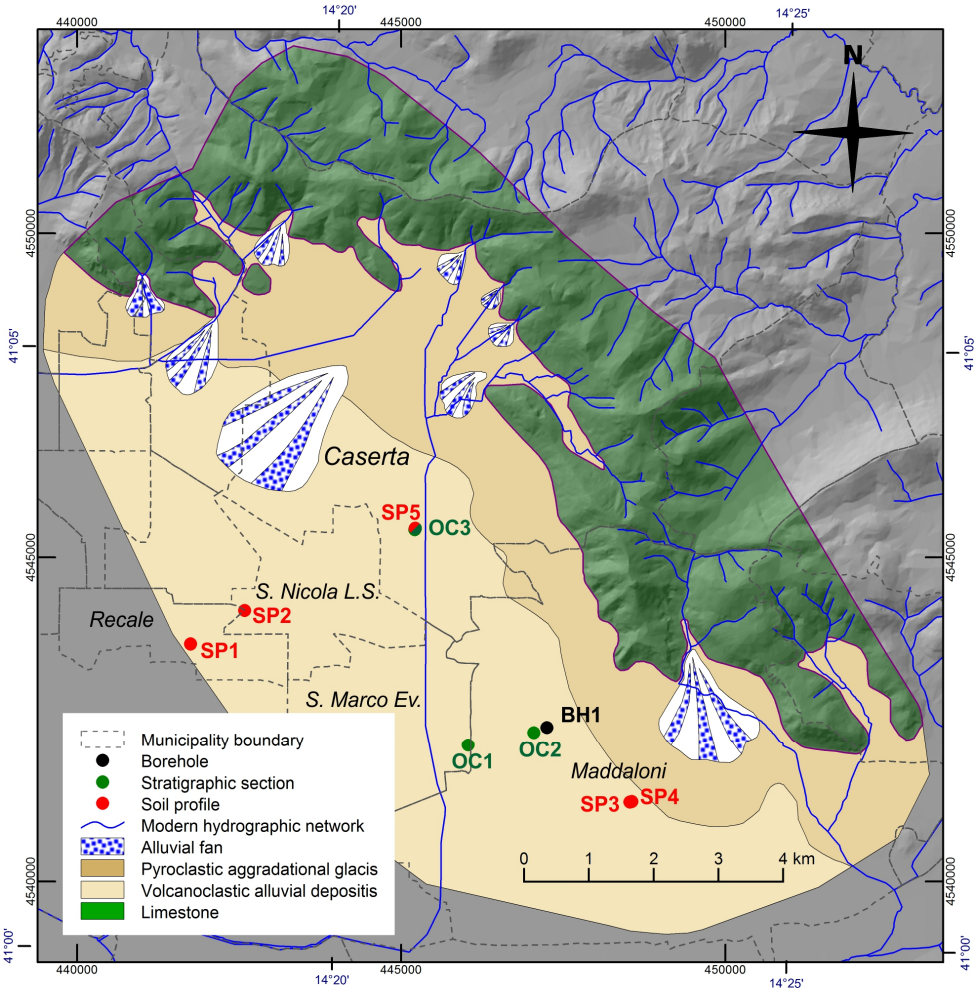

Figure 2. Schematic geological map of the study area (based on [17]). Location of the studied soil profiles and lithostratigraphies.

The study area is nowadays characterized by a Mediterranean climate with an average annual precipitation of about 1000 mm and an average annual temperature of 16 °C [32]. Land surfaces are mainly characterized by urban and artificial land covers, industrial crops, horticultural crops, and fruit tree plantations. Land areas with more natural conditions, such as natural grasslands, broad-leaved forests, and sparsely vegetated areas, occupy only limited surfaces [33].

3. Materials and Methods

We selected five sites at an elevation ranging from 37 to 58 m a.s.l., on which five soil profiles were studied: SP1, SP2, SP3, SP4, and SP5 (Figure 2; Table 1). Three of them (SP3, SP4, and SP5) were on uncultivated surfaces. SP1 has not been tilled for about 20 years. SP2 was used until 1985 as a walnut plantation, which was substituted with a fruit plantation until 1993 and was then replaced by maize and tobacco plantations.

The soils were excavated to a depth of at least 200 cm; SP3 and SP4 soil profiles were studied on a surface delimiting a tuff quarry; the SP5 soil profile was documented from an exposure of an appropriate section created by excavations for building construction.

Based on the characteristics listed above, we identified and designated the soil layers approximately parallel to the soil surface, i.e., the so-called master horizons, which are the soil layers distinguishable from adjacent layers by a distinctive set of pedogenetic characteristics [2,34]. The morphological features described in the field were the horizon or layer depth, color (using the Munsell color charts), texture (the weight proportion of the

separates for particles less than 2 mm in diameter, i.e., fine earth, which is conventionally separated in sand, silt, and clay), rock fragments (pieces of geological material 2 mm in diameter or larger, which have resistance to rupture), structure (the natural arrangement of the soil particles into aggregates, characterized by a grade, which is the distinctness of units composed of primary particles, size, ranging from <1 mm to ≥50 mm, depending on the kind, and kind, which is the structure shape), consistency (soil material degree of cohesion and adhesion, or resistance to deformation or rupture), and horizon boundaries (transition from a horizon or layer to the underlying one, recorded by distinctness, which is the thickness of the transition, and topography, which is the shape of the contact between horizons or layers. Distinctness is defined in terms of thickness of the transitional zone as follows: very abrupt, less than 0.5 cm; abrupt, 0.5 to less than 2 cm; clear, 2 to less than 5 cm; gradual, 5 to less than 15 cm; diffuse, 15 cm or more) [2,34,35].

Table 1. Pertinent characteristics of the soil, outcrop, and borehole sites.

Label	Location	Elevation (m a.s.l.)	Geographic Coordinates				Soil Use
			Easting (m)	Northing (m)	Long. Est	Lat. Nord	
Soil							
SP1	Recale	37.0	441,749	4,544,607	14°18′24″	41°3′2″	Meadow grass cultivation
SP2	San Nicola	41.8	442,629	4,544,393	14°19′2″	41°2′55″	Plants for sod production
SP3	Maddaloni	41.9	448,553	4,541,219	14°23′17″	41°1′14″	Sparse shrub vegetation
SP4	Maddaloni	41.7	448,536	4,541,208	14°23′16″	41°1′13″	Sparse shrub vegetation
SP5	Caserta	43	445,213	4,545,418	14°20′52″	41°3′29″	Sparse shrub vegetation
Outcrop							
OC1	S. Marco Evangelista	58	445,214	4,545,426	14°20′52″	41°3′29″	Sparse shrub vegetation
OC2	Maddaloni	46	447,048	4,542,290	14°22′12″	41°1′48″	Sparse shrub vegetation
OC3	Caserta	43	445,214	4,545,426	14°20′52″	41°3′29″	Sparse shrub vegetation
Borehole							
BH1	Maddaloni	47.9	447,048	4,542,290	14°22′12″	41°1′48″	Sparse shrub vegetation

To detect LDs, the volume and composition of the mineral soil fraction ≥2.0 mm (rock fragments, as defined above) were unraveled [1,8]. This fraction was selected because it represents the primary parent material suitable for identifying the origin of the soil horizons. On bulk samples collected from each horizon or layer of four selected soil profiles, SP1, SP2, SP3, and SP4, the evaluation of the volume and the description of the lithological characteristics of the ≥2.0 mm fraction (rock fragments) was performed as follows: the air-dried whole soil samples were gently ground; a known volume of each whole soil sample was sieved to separate the ≥2.0 mm fraction. The separated fraction was transferred into a container with a known volume; its content was measured and related to the volume of the whole soil sample [36]. The separated ≥2 mm fraction was used to implement a description of the lithological characteristics examined in the field through the evaluation of the fragment kinds, their dominant size, roundness, shape, color, and apparent alteration degree [2,34].

The investigation was completed using four lithostratigraphies that were selected from literature and reinterpreted in pedological key. They included three stratigraphic sections: OC1 [37], reported by [17,38] and [25], OC2 [38], OC3 [17], and one borehole: BH1 [25].

Pertinent characteristics of the soil profile and lithostratigraphy locations are listed in Table 1. The lithostratigraphy description is reported as a part of the results of the present investigation only for the benefit of the manuscript organization.

4. Results

4.1. Lithostratigraphic Sequences

Figure 3 shows the general stratigraphic pattern reconstructed from the cited literature. From the top to the bottom, the sequences are organized as follows:

Unit I: Post-NYT soil and colluvial sediments.
Unit II: Multistratified pyroclastic unit (NYT).
Unit III: Post-CI soil and/or colluvial/alluvial sediments.
Unit IV: Tuff unit (CI).

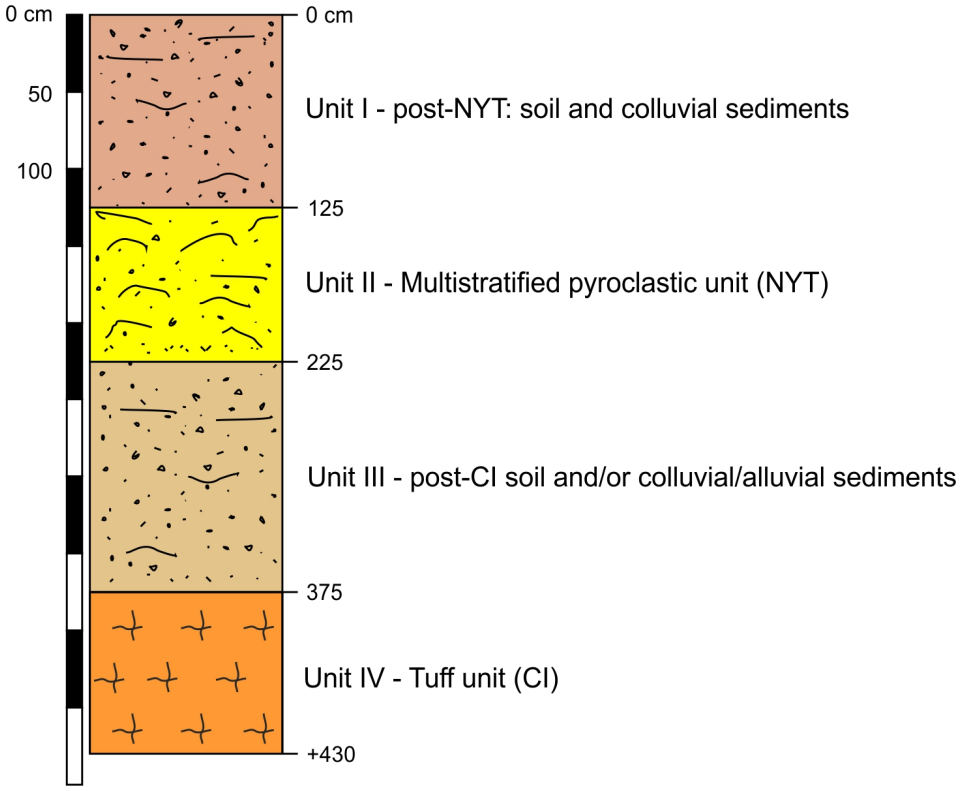

Figure 3. Sketch of the general pattern of the lithostratigraphic units reconstructed based on the selected literature (OC1, OC2, OC3, and BH1). The thicknesses of the first three portions are the mean of those reported in each section considered.

Unit II and IV were considered marker levels attributed to the Phlegrean eruptive phases and recognized over the entire study area.

Unit II consists of white and gray pumice layers alternating with white ashy layers, the deepest of which everywhere marks the base of this pyroclastic unit; the thickness ranges from 50 to 150 cm.

The CI products (Unit IV) are characterized by vertical and lateral facies changes, varying from the yellow zeolitized tuff facies (recognized in the OC1 section) to the gray tuff facies (present in the OC3 and OC2 sections).

In all analyzed sections, the CI deposit was separated from the upper NYT by a thick depositional unit, which varies in thickness from 100 to 200 cm (Unit III). In the OC1 section, it consists of a brown paleosol; in the OC2 and OC3 sections, the paleosol is also accompanied or substituted by a level of colluvial and/or alluvial sediments. In particular, in the OC3 section, these latter were described as a pedogenized level, which consisted of discontinuous deposits of altered pumices in the pyroclastic matrix, where the characteristics of these reworked pumices suggested the participation of CI products in the formation of the level in question [16]. The effects of sediment mobilization post-CI were also recorded in the BH1 borehole in which the deepest horizons, although apparently linked to the underlying CI substratum, were separated from this latter by an erosional surface [18].

Unit I consists of a pedogenized portion varying in thickness from 100 to 150 cm, resting on the NYT products. In the OC2 section, a massive yellowish pumiceous level was described resting on Unit II, although it is not attributable to NYT. In the OC3 sequence, this

upper Unit is separated from the underlying NYT products by a colluvial level described as a whitish and yellowish ashy matrix, which showed a gradual transition into the uppermost pedogenized cover.

4.2. Soil Profiles

4.2.1. Morphological Characteristics

As an effect of the pedogenesis, the soil bodies result in a sequence of identifiable horizons and layers, which contain the marks of the processes responsible for their formation. The pedological approach [2] points out the different pedogenetic processes, discriminating among the possible steps of soil formation through an accurate description of the portions of the surfaces involved in the pedogenesis.

Based on these considerations, in Figure 4, we depict a general pattern of the studied soil profiles, whose morphological features are reported in Table 2. This sequence of the soil horizons results from the information surveyed in the field and from that deriving from the laboratory analyses conducted on the rock fragment fraction ($\geq$2 mm), reported further on. It is important to underline that from this point, the term "Unit" applied to soils will only be used to quickly identify the single soil portions and their related horizons or strata and to facilitate the comparison with the Stratigraphic Units sketched in Figure 3.

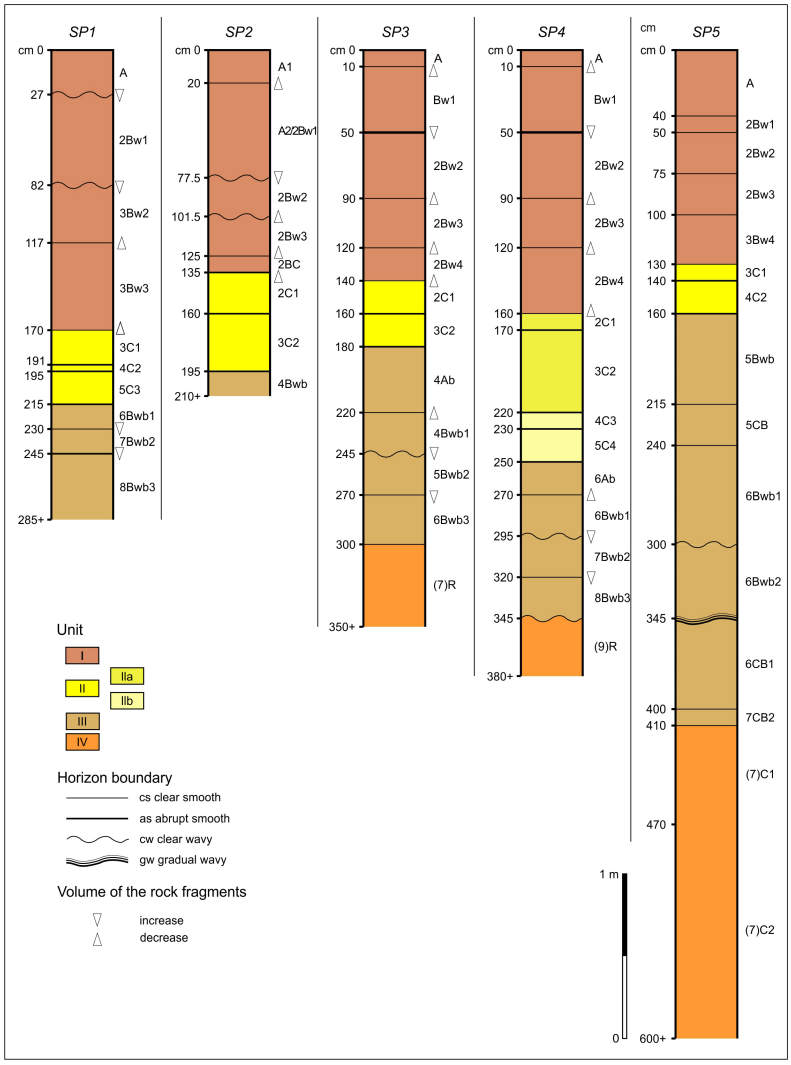

Figure 4. Pedostratigraphy of soil profiles. The morphological features of each soil profile are reported in Table 2. The soil profiles are characterized by lithological discontinuities: these are contacts between

horizons with significant changes in particle size distribution or mineralogy, that represent differences in lithology within a soil [2]. The lithological discontinuity is the horizon designed by a number prefix which precedes the capital letter of the horizon (A, B, . . .). Horizons designed by two different number prefixes (in ascending order from the top to the bottom) are lithologically discontinuous horizons [2]. In SP5 soil profile, the two deepest (7)C1 and (7)C2 soil layers of Unit IV are another facies of Campania Ignimbrite. Volume of rock fragments: the two symbols mean that the volume of the rock fragments increases or decreases from a horizon to the overlying one. In SP2 profile the A2/2Bw1 horizon was composed by two parts: the A2 and the 2Bw1. The genetic discontinuity between the A2 horizon portion and the underlying 2Bw2 horizon was due to the higher rock fragment content and the different composition in A2 with respect to the underlying 2Bw2. By contrast, the composition of the 2Bw1 horizon portion, in which the content of rock fragments did not significantly vary with respect to the underlying horizon, was similar to that of the underlying 2Bw2 horizon, indicating genetic continuity between this 2Bw1 horizon portion and the underlying 2Bw2 horizon. Further, the rock fragments contained in the upper A1 horizon decreased with respect to the A2 portion of the underlying A2/2Bw1 horizon and were similar those contained in horizon portion in question, indicating genetic continuity between the A1 horizon and the underlying A2 horizon portion.

Table 2. Morphological characteristics and rock fragment volume of the studied soils.

Soil	Unit	Horizon	Depth (cm)	Dry Munsell Color	>2 Mmfragments [a] and Texture [b]	Structure [c]	Consistency [d]	Boundary [e]	>2 mm Fragments (% vol)
SP1	I	A	0–27	2.5Y 4/4	fg ls	4 m/c abk	mfi/fi	cw	24
		2Bw1	27–82	2.5YR 5/4	f/vf sl	3 m/c abk/sbk	mfi	cw	14
		3Bw2	82–117	2.5Y 5/6	f/m l	2/1/0 m/f sbk/abk	fr	cs	7.3
		3Bw3	117–170	2.5Y 5/4	c/m/fg sl	1/2 f/msbk/abk	vfr	cs	16.6
	II	3C1	170–191	2.5 Y 7/2	m/c/fg sl	0/2	lo/mfi	as	20
		4C2	191–195	10YR 7/2	f/m vg sl	0	lo	as	50
		5C3	195–215	2.5Y 7/2	m/c vg l	0/1 ma	lo/vfr	as	46.0
	III	6Bwb1	215–230	2.5Y 4/4	m/f sl	2 f/m/c sbk	vfr	cs	13
		7Bwb2	230–245	2.5Y 5/4	m/f l	1/2 f/m sbk	vfr	as	7.4
		8Bwb3	245–285+	2.5Y 4/4	f sl	1/2 m/f sbk	vfr	-	3.7
SP2	I	A1	0–20	2.5Y5/4	vf/f ls	3/4 f/m/vc sbk/abk	fr/mfi/fi	cs	3.7
		A2/2Bw1	20–77.5	2.5Y 4/2	vf/f/ls-	3/1/2 c/vc/f sbk/abk	lo/mfr/mfi	cw	7.6–4.5
				2.5Y4/4	f/m/vf sl				
		2Bw2	77.5–101.5	2.5Y 5/6	f/m/vf/sl	2 c/m/f abk/sbk	mfr	cw	4.2
		2Bw3	101.5–125	2.5Y 5/4	m/f sl	1 f/m abk/sbk	lo/vfr	cs	9.3
		2BC	125–135	2.5Y 7/4	f/m/cg sl	0/1/2 f/m sbk	lo/vfr	as	25
	II	2C1	135–160	10YR 7/2	f/m/c eg sl	0	lo	as	62.5
		3C2	160–195	2.5Y 7/2	m/f vg l	0/1 ma	lo/vfr	as	55
	III	4Bwb	195–210+	2.5Y 4/4	m/f sl	2 m/c sbk/abk	mmi	-	14
SP3	I	A	0–10	2.5Y 4/4	vf/f sl	0/2 vf/f sbk/gr	lo/vfr	cs	10
		Bw1	10–50	2.5Y 5/4	vf sl	4/3 m sbk	mfi	as	12
		2Bw2	50–90	2.5Y 5/6	vf/f l	3 c/m sbk/abk	mfi	cs	4
		2Bw3	90–120	10YR 6/6	vf/f/m l	2 m/c abk/sbk	mfi	cs	8
		2Bw4	120–140	10YR 6/4	f/m vg l	1 m/c/vc abk/sbk	mfr	cs	36
	II	2C1	140–160	10YR 7/3	m/f/c gr sl	0	lo	as	92
		3C2	160–180	10YR 7/2	m/f l	0/1 ma	lo/fr	as	8
	III	4Ab	180–220	10YR 6/3	f vg ls	2 m/f abk/sbk	fr	cs	48
		4Bwb1	220–245	10YR 5/4	f/vf vg sl	2 m/f abk	fr	cw	52
		5Bwb2	245–270	10YR 6/3	f/vf g l	2 m abk	mfr/fr	as	23
		6Bwb3	270–300	10YR 6/4	vf/f sl	vf/f 2 m abk/sbk	mfr/fr	cs	14
	IV	(7)R	300–350+	-	-	-	-	-	-
SP4	I	A	0–10	2.5Y 4/4	vf/f sl	0/1/2 f sbk/gr	vfr	cs	10
		Bw1	10–50	2.5Y 5/4	vf g sl	3/4 m sbk	mfi	as	15
		2Bw2	50–90	2.5Y 5/6	vf/f l	3 m sbk/abk	mfi	cs	5
		2Bw3	90–120	2.5Y 6/6	vf/f/m l	2 m/c abk/sbk	mfi	cs	8
		2Bw4	120–160	2.5Y 6/4	m/f/vf g l	2/1 m/c/vc abk/sbk	mfr/mfi	cs	30

Table 2. *Cont.*

Soil	Unit		Horizon	Depth (cm)	Dry Munsell Color	>2 Mmfragments [a] and Texture [b]	Structure [c]	Consistency [d]	Boundary [e]	>2 mm Fragments (% vol)
	II	IIa	2C1	160–170	10YR 7/3	m/f/c eg sl	0	lo	as	90
			3C2	170–220	10YR 7/2	m/f l	0/1 ma	lo/vfr	as	10
		IIb	4C3	220–230	-	vf/f s	0	lo	as	abs [1]
			5C4	230–250	-	vf/f s	0	lo	as	abs [1]
	III		6Ab	250–270	10YR 6/3	f vg ls	2 m/f abk/sbk	fr	cs	45
			6Bwb1	270–295	10YR 5/4	f/vf vg sl	2/3 m sbk	fr	cw	54
			7Bwb2	295–320	10YR 6/3	f/vf g	2/3 m abk/sbk	mfr/fr	as	25
			8Bwb3	320–345	10YR 6/4	vf/f sl	2/3 abk	mfr/fr	cs	12
	IV		(9)R	345–380+	-	-	-	-	-	-
SP5	I		A	0–40	2.5Y 3/4	vfg ls	2 m/f abk/sbk	fr	cs	-
			2Bw1	40–50	2.5YR 4/4	f ls	2 m/f sbk/abk	mfr	cs	-
			2Bw2	50–75	2.5Y 4/5	f/m ls	2 m/f/c sbk	fr	cs	-
			2Bw3	75–100	2.5Y 5/4	f/m ls	2 m/c sbk	fr	cs	-
			3Bw4	100–130	2.5 Y 6/2	m/fg sl	2/1 c/m sbk	fr/mfr	cs	-
	II		3C1	130–140	10YR 6/2	m/fg sl	0/1 m/f sbk	fr	as	-
			4C2	140–160	2.5Y 7/2	c/m/fg l	0/1 m/f/c ma	lo/vf/mfi	as	-
	III		5Bwb	160–215	2.5Y 3/4	f/m ls	2 m/f sbk/abk	fr	cs	-
			5CB	215–240	2.5Y 4/4	m/f vg s	0/1 f/m sbk	lo/vf	cs	-
			6Bwb1	240–300	2.5Y 3/4	vf ls	1 m/f sbk/abk	fr	cw	-
			6Bwb2	300–345	10YR 3/4	f sl	1 m/f abk/sbk	fr	gw	-
			6CB1	345–400	10YR 5/4	fg s	1 m/f abk	fr/mfr	cs	-
	IV		7CB2	400–410	10YR 6/3	m/fg s	1 m/f abk	mfr	cs	-
			(7)C1	410–470	-	-	-	-	-	-
			(7)C2	470–600+	-	-	-	-	-	-

[a] >2 mm fragments = g = gravelly, gr = gravel; e = extremely, v = very, f = fine, m = medium, c = coarse. [b] Texture = ls = loamy sand, sl = sandy loam, l = loam, s = sand. [c] Structure = Grade: 0 = structureless, 1 = very weak, 2 = weak, 3 = moderate, 4 = strong; Size: f = fine, m = medium, c = coarse, vc = very coarse; Kind: gr = granular, abk = angular blocky, sbk = subangular blocky, ma = massive. [d] Consistency = lo = loose, vfr = very friable, fr = friable, mfr = moderately friable, mfi = moderately firm, fi = firm. [e] Horizon boundaries = Distinctness: a = abrupt, c = clear, g = gradual; Topography: s = smooth, w = wavy. [1] abs = absent. The slashes mean that on the same horizon, there are different sizes and kinds of coarse fragments and different structures and consistencies. The number prefix in parenthesis indicates the possible discontinuity of the R layer with respect to the overlying horizon.

All soil profiles were at least 2 m deep. Unit IV in SP3 and SP4 soil profiles consisted of a zeolitized lithified tuff, yellowish in color, with sparse columnar jointing and a pipe structure (Figure 5b,c).

In all soil profiles (on Unit IV where present) a first pedogenized portion (Unit III) occurred (Figure 5a,c). The soil profiles that better exhibited Unit III (SP1, SP3, SP4, and SP5) consisted of buried soil horizons (Ab, Bwb, and CB), with a total thickness varying from 70 to 120 cm. Variable proportions of volcanic lithics and pumices, with some loose, fragmented crystals, constituted the rock fragment fraction of these buried soil horizons. Mainly sandy loam textures and clear or abrupt horizon boundaries were mainly found. In a position like that occupied in the soils by the buried horizons, a paleosol level is recognized on the land surface extending from the Phlegrean Fields to the Campania Plain [39,40], as well as in the reported lithostratigraphies. In some of them, it also occurred above a colluvial layer [16,25,38].

On Unit III, multiple C soil horizons were present (Unit II) (Figure 5a,c), which corresponded to a stratified pyroclastic package. It had the following main features: it consisted of one level of pumices and subordinate lithics, or a level of dominant welded ashes over a pumice stratum, which was superimposed on a laminated ash level; it varied in thickness from 30 to 60 cm. In the SP4 soil profile, at the bottom of Unit II, there were two thin strata of pyroclastics (Unit IIb). The textures were mainly sandy loam and loam. Horizon boundaries were abrupt.

As also in the lithostratigraphic sequences, on Unit II, an uppermost pedogenized portion, Unit I (Figure 5a,c), consisting of A, Bw, and BC soil horizons, completed the profiles on their top. In the soils, the thickness of Unit I ranged from 135 to 170 cm. The texture was sandy loam, loamy sand, and loam. The horizon boundaries were mainly

clear. Also here, pumices and volcanic lithics, in variable proportions, compose the rock fragment fraction.

No horizon of the studied soil profiles exhibited clay illuviation or concretions.

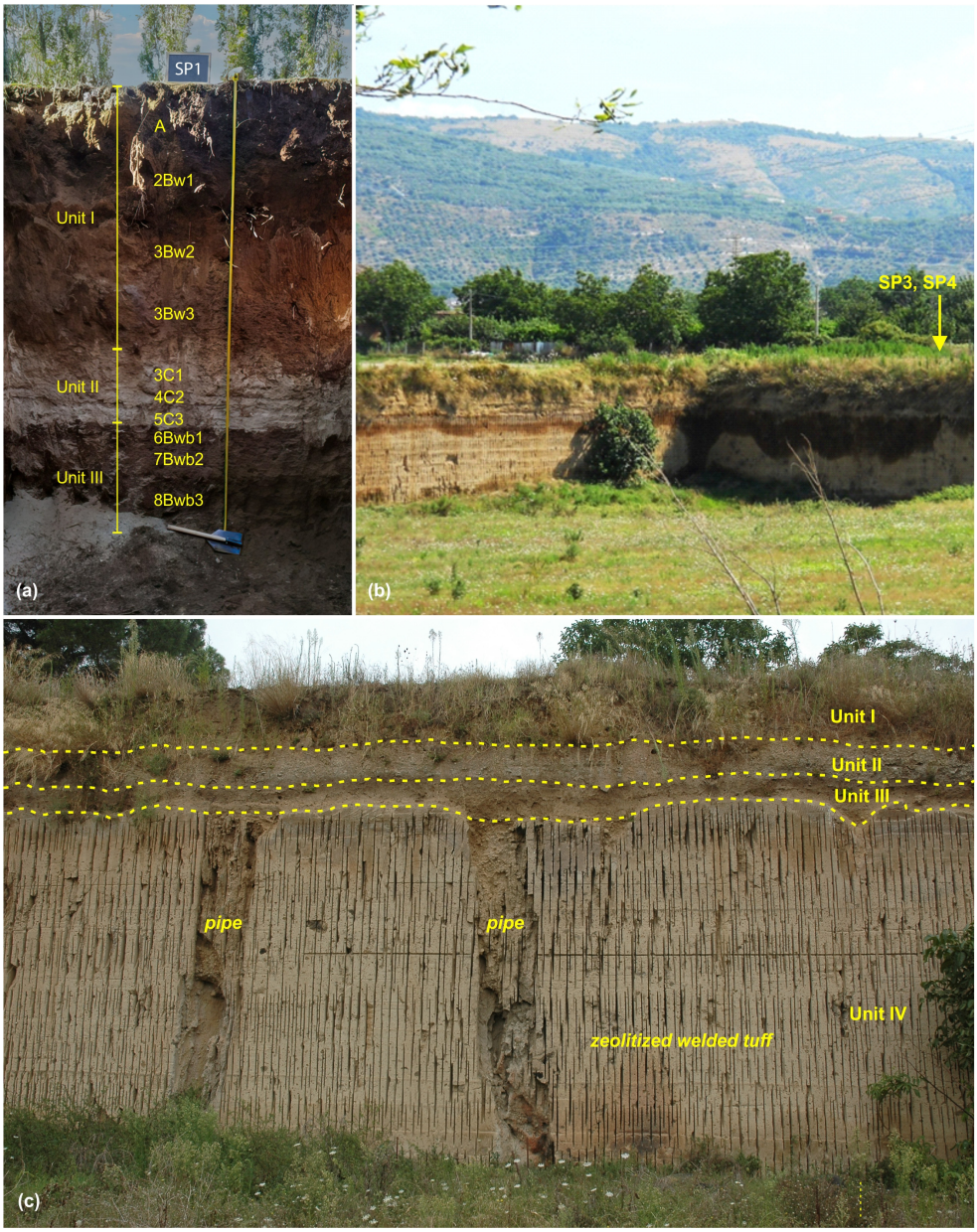

Figure 5. Field characteristics of the soil profiles. (**a**) SP1 soil profile. Unit II (C soil horizons) consisted of a stratified pyroclastic package from the products of NYT. (**b**) Overview of the location of the SP3 and SP4 soil profiles, showing the outcrop corresponding to the excavation area and the relieves bordering the study area. (**c**) Detail of the outcrop in (**b**), exhibiting Unit IV (R horizon consisting of zeolitized lithified tuff with evident pipe structures) and the continuous whitish layer of NYT products (Unit II).

4.2.2. Laboratory Analyses

The results of the analysis of the rock fragment volume conducted on soil samples from the selected SP1, SP2, SP3, and SP4 soil profiles are reported in Table 2. In accordance with field observations, variations in rock fragment content were recorded along Unit III of SP1, SP3, and SP4 soil profiles. In this Unit, the volume increased from the 8Bwb3 to 6Bwb1 horizons of SP1, from 6Bwb3 to 4Bwb1 horizons of SP3, and from 8Bwb3 to 6Bwb1

horizons of SP4. In contrast, in this Unit, the content decreased from 4Bwb1 to 4Ab in SP3 and from 6Bw1 to 6Ab in SP4. Unit IIa consisted of two or three C pyroclastic soil layers, whose rock fragment content depended on the texture of this primary pyroclastic material [39]. Variations in rock fragment content were also detected in Unit I. In particular, in SP1, from the bottom to the top, after the decrease recorded in the 3Bwsoil horizons with respect to the underlying 3C1 pumiceous layer (Unit II), an increase in the volume of the rock fragments was measured from the 3Bw2 to the 2Bw1horizon and from this latter to the A horizon; in SP2, after the decrease recorded in 2CB and 2Bw horizons, an increase was seen from the 2Bw2 horizon to one part (A2) of the overlying A2/2Bw1, and a decrease from this part to the uppermost A1 soil horizon; in SP3 and SP4 profiles, after the decrease recorded from the 2C1 horizon (Unit II) to the overlying three 2Bw horizons, rock fragment increment was detected from the 2Bw2 to the overlying Bw1 horizon. A small decrease in the rock fragment content was seen in the uppermost A soil horizon of weather SP3 or SP4.

The evaluation of the genetic relationships among soil horizons was completed using the observation of the composition of the rock fragment fraction. As an example, we report the results related to the horizon sequence of the SP1 soil profile (Figure 5a). From the bottom to the top, the analysis of the rock fragments of the deepest 8Bwb3 horizon of Unit III showed that in such a horizon, the fraction in question consisted mainly of fine pumices (about 0.5 cm) and lithics and that pumices were brownish, with some whitish elements, rounded and strongly weathered. In the overlying 7Bwb2 soil horizon, which had recorded an increase in the content of the rock fragments compared to the underlying 8Bwb3 horizon, most of the fraction is composed of pumices with a larger size (up to about 1.5 cm), grayish and whitish in color, mainly angular, with a high degree of alteration. In the 6Bwb1 horizon, recording a further increase in the rock fragment content, particles mainly consisted of medium and fine, rounded and elonged, brownish altered pumices. The layers constituting Unit II, lying on the 6Bwb1 horizon, had the most abundant (up to 50%) and coarsest rock fragments (up to 5 cm) along the soil profile. This Unit consisted, at the bottom, of a very gravelly ashy layer (5C3 horizon) underlying a thin pumiceous layer (4C2 horizon) and, at the top, a gravelly 3C1 horizon in which the rock fragments consisted of angular and elonged ashy elements, subordinate lithics, and mainly gray pumices (up to about 2 cm). These components, in a lower content, also constituted the pedogenetic substratum of the two 3Bw soil horizons of the overlying Unit I in which, nevertheless, they had sizes from a few mm up to about 1.5 cm and were covered by a yellowish coating; no differences were detected among rock fragment fractions of the two 3Bw soil horizons, except for the size (max about 1.0 cm) of the fragments of the 3Bw2 horizon, which were smaller than those of the underlying 3Bw3 horizon. In contrast, a distinctly different composition of the increased rock fragment fraction was found in the 2Bw1 soil horizon, in which very fine and fine elements (max 0.5 cm) were mainly brownish altered rounded pumices, with only a few lithics. This composition also differed from that of the A soil horizon, where a higher amount of lithics and the occurrence of whitish pumices, in addition to brownish altered ones, contributed to the further measured increment in the rock fragment content (see Supplementary Materials S1 for information on the other soil profiles analyzed).

Other features which, even if with caution, could be invoked to better understand the genetic relations among the soil horizons were color and structure. In particular, in Unit III of the SP1 soil profile, the 8Bwb3 horizon had a darker color (2.5Y 4/4) compared to that of the overlying 7Bwb2 horizon (2.5Y 5/4), which suggested a break in the expected increase in organic matter from the bottom to the top of the soil. With respect to the soil horizon structure, in Unit I of the SP2 soil profile, the A1 and the A2 part of A2/2Bw1 displayed a chaotic and sometimes firm aggregation of soil portions, in contrast with the angular and subangular rocky structure, which had a grade from moderate to weak, characterizing the contiguous soil horizons. Finally, in the soil profile in question, there was an A2/2Bw1 combination soil horizon, which is a horizon with two distinct parts that have recognizable properties of two kinds of master horizons indicated by capital letters [2]: the presence

of this horizon provided a signal of the participation of two different soil masses to the formation of the soil in question.

5. Discussion

5.1. Soil Horizonation Settlement

All soil profiles were developed from volcanic materials that constituted the particles of all soil horizons and layers in accordance with the wide distribution of volcanic substrata in the study area. In particular, one of the main features of the horizonation of the studied soils was the multi-storied arrangement resulting in two multileveled pedogenized portions, such as those of Unit II and Unit IV, which were separated by a stratified pyroclastic bed (Unit III). The organization, position, composition, and thickness of this soil portion indicated that it consisted of the distal fall and surge deposits of NYT eruption [39–41], as also found in the stratified pyroclastic package surveyed in the lithostratigraphic sequences reported above. Unit IIb, occurring in SP4, was not clearly referable to NYT fall materials, and it could be the result of erosion activity accumulating loose volcanic materials on the soil location during the time. Unit IV was intercepted and closed, in turn, the soil profiles at the bottom. It showed the position and characteristics of the zeolitized facies of the CI deposit, outcropping in some portions of the Campania Plain as a modification of the widespread Campania Ignimbrite gray facies [42,43]. Accordingly, this deposit was always recorded at the bottom of the lithostratigraphies reported in the present investigation, corroborating its correspondence with the R horizon of the studied soil profiles in which it was surveyed. The increasing depth of the CI products toward the west in the studied area [25,30] was likely responsible for their absence in the soil horizonation of SP1 and SP2: these soil profiles, in fact, were in areas where the CI upper surface is deeper than the lower boundary of the related pit excavation. In the SP5 soil profile, this Unit consisted of two levels, which were different facies of the CI.

This pedostratigraphic framework depicted a pathway in which, in the first instance, there were at least two pedogenetic intervals, each of which occurred after the deposition of the respective underlying primary volcanic products, in analogy with the reported lithostratigraphic sequences sketched in Figure 3. A pedostratigraphic organization like this typically characterizes the volcanically influenced environments in various parts of the world, where different tephra intermittently cover the existing landforms, substantially contributing to soil formation ([36,44–48], among others). In these environments, soils are generally characterized by the so-called andic soil properties [49]. These are properties that develop, to various extents, from the weathering, mainly at the expense of glass components [44]. In these contexts, the soils can constitute interesting paleomarkers according to the different conditions of formation and evolution [50]. The morphological features of the studied soil profiles also excluded mechanisms of water infiltration and circulation able to promote the dispersion and flocculation of clay particles and formation of clay coatings, as well as hydromorphic conditions affecting the mobile elements and forming concretion or nodules, which are documented in other pedological environments ([50] and references therein).

The second feature of the surveyed soils concerned the genetic relationships among the soil horizons and strata, which have been inferred by the mutual variation along the soil profile, of rock fragment content and composition, and by the other reported morphological features. As a general rule, rock fragment content can vary from the bottom to the top of a soil profile as a result of three mechanisms, such as (1) weathering from the parent material, which can favor the decrease in the volume of fragments from the parent material to the surface; (2) biological displacement, which can be responsible for variations in the rock fragment volume in upper horizons, mainly through tree uprooting or faunal activities; (3) sediment additions from transport and redistribution processes, which, besides those operating by humans, are important when geomorphic conditions promote material transport and redistribution from adjacent sites on existing surfaces [51,52].

In the studied soils, there were no evident marks of biological displacement, except for the possible anthropic contribution to Unit I of the SP2 soil profile, which was only deduced from the local agriculture history. So, two mechanisms could be responsible for the decrease in the rock fragments: the weathering of the parent material or the addition of sediments with a content of rock fragments lower than that of the horizon on which the sediments are deposited. In the analyzed cases, all horizons displaying the decrease in question had lithological constitutions like that of the respective underlying horizons but with marks of weathering of the original mineral components: this suggested that, in such cases, the weathering process was the most probable mechanism, and this implicated genetic continuity between the involved soil horizons. Unlike the decrease, a unique mechanism could explicate the rock fragment increase from a horizon to the overlying one in the studied soils: the sedimentary input from the neighboring slopes. This indicated that supplemental materials also contributed to soil formation, generating lithological discontinuities, as recorded in Table 2 by the devoted horizon designation. As a result, in the studies of soil profiles, in addition to weathering processes, there were constructional events determined by the introduction of both the primary volcanoclastic and reworked soil materials.

5.2. Pedological Signature of Sedimentary–Geomorphic Processes in the Studied Area

In Figure 6, the genetic correspondence among the horizons of the different soil profiles is depicted. Lithological discontinuities marked the studied soil profiles in two ways: in correspondence with the transition from the soil horizons of Unit III to the overlying C horizons of Unit II, consisting of NYT pyroclastics, and among some of the horizons constituting Unit I and those of Unit III. The first case of discontinuities was the expected effect of the introduction on the surfaces of new primary pyroclastic material (C soil horizons). The second case of discontinuities was that which interrupted the genetic sequence in the pedogenized "Units". This suggested that surfaces have suffered additional periodic inputs of materials other than those deriving from the primary volcanic products. In line with the location of the studied soils on a plain surrounded by mountain relief, these materials would have been introduced into the pedostratigraphies through processes of transport and the redistribution of sediments.

They buried the surfaces during the interval from the CI and NYT pyroclastic deposition and after the sedimentation of NYT pyroclastics until the present. Involving more episodes of the addition of materials contributed to soil construction.

These pedo-sedimentary dynamics developed during the succession of the Late Quaternary abrupt climatic events ([53,54] and references therein), especially those linked to the Last Glacial–Interglacial Transition [55]. The climatic evolution at the LGIT is characterized by multiple episodes of climatic instability, which are often difficult to interpret in the patterns of climatic and environmental changes recorded in the sedimentary sequences, especially where precise stratigraphic constraints are absent. However, it should be highlighted that the environmental and landscape response to these oscillations, on a global scale, has often shown an increase in clastic sedimentation during climate deterioration, suggesting catchment erosion; the return to favorable climatic conditions is usually associated with a reduction in clastic sedimentation through reduced allogenic sediment loading and increased catchment stabilization [54].

Even though precise dating of the horizons described is not available, the succession of the pedostratigraphic events can be framed within the context of the climatic evolution mentioned above, considering the studies carried out on the Campanian Plain by [20,22,56,57]. In particular, it has demonstrated that during the CI emplacement, the sea level was lowered following the Last Glacial (LG) period, and, during the maximum of the LG, the upper surface of this unit was eroded by river down cutting [20,57,58]. It is known from the ice core chronology that during the boundary of the Last Glacial Maximum and the Holocene, the climate varied between alternating centennial warm and cool phases [59], but the record of these changes can be modified or altered by the overprinting of local events,

such as volcanic activity. The emplacement of the NYT surge deposits occurred during this transitional climate phase. The latest Pleistocene–Early Holocene sea level rise resulted in rapid flooding of the lower Volturno Plain with the development of a back-stepping regressive-to-aggrading sedimentation. During the Middle–Late Holocene deceleration of the post-glacial sea-level rise, a prograding deposition took place on the whole plain. The detected lithologically discontinuous soil horizons could be tentatively read in light of the above large-scale climate changes. Nevertheless, the lack of accurate stratigraphic constraints makes it difficult to identify an unambiguous correlation with globally recognized climatic events. Unlike this, the identification of the detected lithologically discontinuous soil horizons constitutes a key for the reconstruction of the dynamics of the surfaces in response to the characteristics of the local geomorphological context.

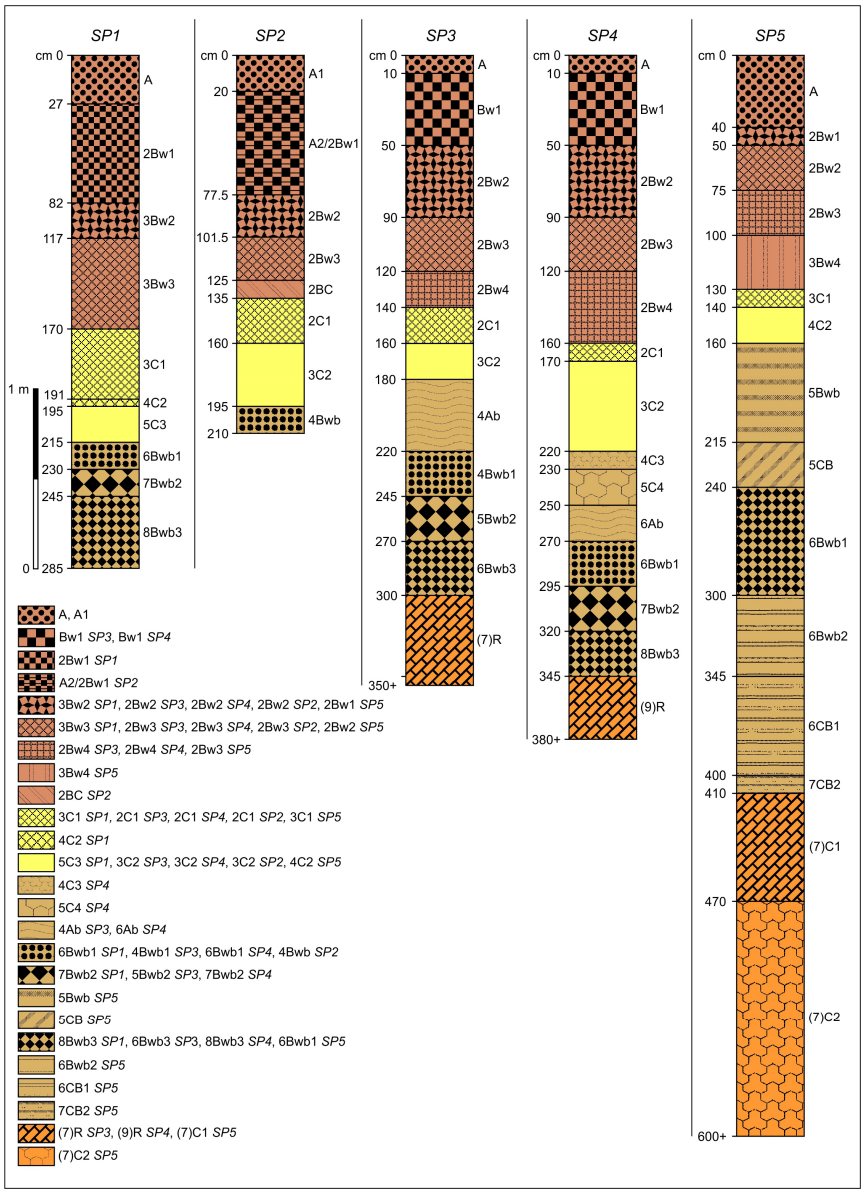

Figure 6. Genetic correspondence among the studied soil profiles. The same drawing depicting the horizons of different soil profiles serves to tentatively correlate the horizons in question in terms of function of their origin and position in pedostratigraphy. The horizons designed by the change of the Arabic number preceding the capital letter of the soil horizon with respect to the number of the underlying horizon have sedimentary origin; the horizons not designed by this change have residual origin (see text for further details).

Overall, however, the results obtained by the pedological investigation were consistent with the reported lithostratigraphic investigations conducted in the study area, which suggested that sediments deriving from runoff and dissection activities post-CI and NYT deposition contributed to the formation of buried and modern soils, as described in the lithostratigraphic sequences. The interpretation of these lithostratigraphic sequences in the pedological key showed the close correspondence between geomorphic–sedimentary events and pedostratigraphic characteristics, as depicted in Figure 7. In particular, the susceptibility of the slopes bordering the Campania Plain to loss and transfer of loose materials, also probably under favorable climatic events [17], contributed to generating colluvial, dendritic, and erosion phases that have been redistributed on surfaces morphologically suitable not only to receive but also to retain sediments: these participated effectively in the construction of the pedological covers, interrupting the "normal top down" pedogenesis from the primary volcanic deposits through the burial of the primary deposits or their pedogenetic products. In the described soil architecture, the identification of "exogenous soil materials" and their differentiation from the "endogenous" ones, as well as their contribution to the comprehension of the surface dynamic construction, provide information on characteristics and properties that can abruptly vary and contrast along the soil profile. This is particularly relevant in the relationship between soil and water. Water, in addition to its primary role as a vector of most of the weathering processes of the mineral components and decomposition of the organic matter, is directly connected to the hydraulic soil properties. The study of the latter, which is one of the main concerns in the rainfall-induced landslide assessment, is a particularly complex task when applied to vertically heterogeneous soils: in these cases, where discontinuities are found to contribute to the infiltration process [60], the investigation of contrasting hydraulic properties [61–66] can highly benefit from the pedological approach.

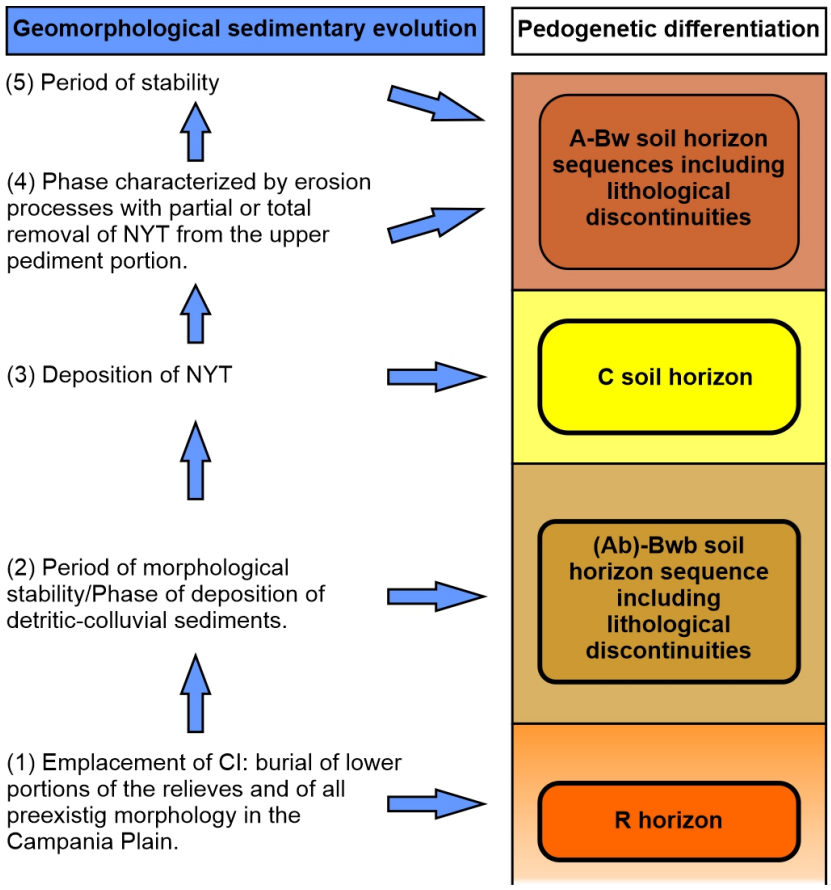

Figure 7. Relation between geomorphic and pedogenetic events in the studied area.

6. Summary and Conclusions

The fundamental concern in studying the soils in the selected portion of the Campanian alluvial plain was to connect their morphology and architecture with the sedimentary–geomorphic processes characterizing the area in question. From this perspective, a key point was offered by the polygenetic volcanic character of the surveyed soils. In fact, the soils were formed via two mechanisms, such as through in situ pedogenetic development from the Phlegrean substrata and through the addition of extra situ materials.

The two factors important for the pedogenesis currently dominating the studied area were as follows: (1) the sedimentary dynamics governing the intermittence and relative temporal intervals among sediment supplies; (2) the almost flat geomorphology of the surface area able to receive and retain the primary Phlegrean tephra, such as the surveyed products of CI and the pyroclastic fall and surge deposits of NYT, the overlying pedogenetic phases related to these primary volcanic sediments, and the sediments transported by alluviation/colluviation episodes coming from the Apennines slopes. All this generated a soil architecture in which genetically discontinuous horizons interrupted the pedogenetic activity from the original substrata. Therefore, the studied pedogenetic covers resulted from top-down processes alternating with the massive and rapid accumulation of both primary tephra and reworked materials, which was closely consistent with the geomorphic–sedimentary events characterizing the studied area. The effects on pedogenesis of the sedimentary–geomorphic processes in the studied context were the growth of the surface thickness, the storage in soils of the original volcanic substrata, and the increment in the polygenetic nature of the soils. The collected pedological evidence also indicated that the factors responsible for soil formation produced a pedogenetic pattern that repeated throughout the surveyed surface. On the one hand, the lack of precise chronostratigraphic constraints does not allow, at this stage of the work, to unequivocally correlate the lithologically discontinuous soil horizons to the climatic variations documented for the Late Pleistocene–Holocene. On the other hand, the results supported the idea that the pedological study implemented by the detection of the soil lithological discontinuities provides an effective clue in the assessment of the relationships existing between the soils and the related geomorphological environment. More generally, the pedological tools in question can be effective in reading and interpreting the phases of the land surface construction in other environments. This is particularly relevant considering the processes involving soil covers in mountain areas. Here, slope inclination forces soil masses to move from one site to another, modifying the primary sequence of the soil horizons and their related properties, which, especially in the environments in question, have important outcomes in surface stability. So, the knowledge of the organization of this soil cover assumes a fundamental role in the comprehension of the mechanisms affecting slope stability and the definition of methods for the control of hazards from rainfall-induced landslides. Finally, future research developments could provide an interpretation of the studied pedological context from a morphoclimatic perspective.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/quat7030039/s1: S1_Soil lithic component.

Author Contributions: Conceptualization: A.E.; methodology: A.E.; software: M.V.; validation: M.V. and A.E.; formal analysis: A.E., R.M., M.V. and P.L.; resources: A.E., R.M., M.V. and D.R.; data curation: R.M., M.V. and A.E.; writing—original draft preparation: A.E.; writing—review and editing: D.R., M.V., R.M. and A.E.; supervision: A.E. and D.R.; project administration: A.E. and D.R.; funding acquisition: A.E. and D.R. All authors have read and agreed to the published version of the manuscript.

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