The "Piscine" coastal depressions of the southern Pontine Plain (Central Italy): evidence from historical cartography and GIS analysis

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Rend. Online Soc. Geol. It., Vol. 69 (2026), pp. …-…, 4 figs., 2 tabs. https://doi.org/10.3301/ROL.2026.10

Short Note

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Citation: Vitale V., Madonna S., Nisio S. & Annunziatellis A. (2026) - The "Piscine" coastal depressions of the southern Pontine Plain (Central Italy): evidence from historical cartography and GIS analysis. Rend. Online Soc. Geol. It., 69, XX-XX, https://doi.org/10.3301/ROL.2026.10.

Guest Editor: Gianluigi di Paola

Submitted: 16 January 2026
Accepted: 31 March 2026

SOCIETÀ GEOLOGICA ITALIANA ETS
FONDATA NEL 1881 - ENTE MORALE R. D. 17 OTTOBRE 1885

ABSTRACT

A multidisciplinary analysis was conducted of numerous surface depressions termed Piscine, exhibiting subcircular morphology. These landforms, which characterized the southern sector of the Pontine Plain (Central Italy), have been documented in historical maps since the eighteenth century, and remain of uncertain origin. To investigate their genesis, bibliographic sources, historical cartography, and geognostic data were integrated to reconstruct the geological and stratigraphic settings in which these depressions developed. These landforms were digitized from pre-reclamation maps and analyzed to explore their distribution patterns and relationships with selected subsurface variables. The results indicate that the depressions are primarily located in areas characterized by outcropping ancient coastal dune sands and display distinct spatial patterns. A consistent spatial correlation was identified between depression density and peat deposit thickness, whereas no clear relationship was observed with fault density. These findings suggest that compaction processes affecting peat-rich sediments, which lead to differential subsidence of overlying deposits, may be a mechanism for depression formation. However, owing to data limitations, alternative processes (piping-related sinkhole activity or dissolution of continental carbonate rocks), cannot be entirely excluded. Further detailed geognostic investigations are required to refine the interpretation and improve the understanding of the subsurface controls governing the development of these landforms.

KEYWORDS: coastal depressions, piping sinkholes, historical cartography, peat collapse, Pontine Plain.

INTRODUCTION

Sinkholes and peat collapse are both subsidence phenomena but differ fundamentally in their geological settings, formation mechanisms, and impacts. In the present study, a multidisciplinary analysis was conducted, focusing on the numerous depressions ("Piscine") that characterized the area before reclamation in the southern Pontina plain and are documented in several historical maps dating back to the eighteenth century (Nisio, 2014). The term "Piscine", adopted from historical cartography, is used here in a descriptive sense and does not imply a specific genetic interpretation.

In particular, the study aims to identify:

a) the interactions between these depressional landforms and the geological–structural framework of the area;
b) the morphogenetic processes responsible for forming the depressions.

This approach aims to clarify the origin of these features and to reconstruct the pre-reclamation geomorphological setting of the Pontine coastal plain, thereby providing insights into subsurface controls in a heavily anthropized lowland environment.

The Pontine Plain is a region in central Italy, bounded by the Tyrrhenian Sea to the west and the Lepini and Ausoni Mountains to the east and north. Its landscape has been shaped by a complex interplay of geological, hydrological, and climatic processes over millennia, including glacial advances and retreats during the Middle and Late Pleistocene, which have left a lasting impact on its topography, hydrology, and ecosystems. The area features marine fossil beaches (fossil dunes) and marshes that developed during the Holocene climatic optimum, processes that continue to influence the landscape today.

The study area is located in the southern sector of the Pontine Plain, between the municipalities of San Felice Circeo and Sabaudia (Latina Province, Lazio Region). From a geological perspective (Fig. 1), the plain represents a subsiding area that developed during the formation of the Apennine chain in the Early Pliocene.

The area is characterized by two main sectors: the first, located northeast of the Sisto River, is composed of continental deposits of coastal, lagoonal, and marshy origin (Pleistocene–Holocene); the second, extending between the Sisto River and the present coastline, consists predominantly of sandy deposits of coastal dune origin (Pleistocene–Holocene) (Brunamonte & Serva, 1990; Barbieri et al., 1999; Marra et al., 2014, 2019; Paone, 2023; Sevink et al., 2023; Van Gorp et al., 2020). Based on deep borehole and geophysical data, these deposits overlie a substratum composed, depending on the sector considered, either of Jurassic–Cretaceous carbonate successions or of Cenozoic Umbro-Sabina succession deposits.

The tectonic framework of the area is defined by Apenninic and anti-Apenninic structural trends that, since the Pliocene, have produced a typical horst-and-graben architecture (Malinverno & Ryan, 1986; Di Filippo & Toro, 1980; Doglioni, 1991; Carminati et al., 2005; Liperi et al., 2011; Marra et al., 2019). The deep structure of the Pontine Plain is controlled by a fault system with a stepwise shape, consisting of segments up to 10 km long. These segments exhibit minimum displacements of 500–600 m near Norma and 600–700 m at La Catena, with the possibility of larger structural offsets (up to 0.8–1 km), similar to those observed in the Ausoni Mounts (Gori et al., 2024). Overall, this area region is characterized by a graben structure filled with Holocene peat and Fe-rich clayey sediments. Peat is very porous and can compress and "collapse" if any of the physical properties of the soil (e.g., pore space, organic matter, and mineral matter content) are compromised.

The plain presents of a series of marine terraces along the coast and an inland lagoon, which was gradually filled with lagoonal sediments, transforming it into the historically known Pontine marshes. Marra et al. (2019) have identified three marine terraces at elevations of ~35 m, ~23 m, and ~12 m a.s.l., Based on geochronologic constraints from 40Ar/39Ar and ESR/U-series dating, these authors correlate these terraces with the sea-level highstands of MIS 5.5, 5.3, and 5.1, respectively. According to Attema (2010, 2017) and Feiken (2012), the lagoon was still open during the Bronze Age, 259–280, and Fig. 9.2 on the palaeography of the Pontine plain. The lagoon was gradually filled in with lagoonal sediments turning it into a swamp as the marine terraces impeded drainage of rivers originating in the hinterland and water coming from springs at the foot of the Lepini mountains (Kamermans, 1991; Sevink et al., 1984). From about AD 500, colluvium emanating from the Ausoni began to cover part of the southern peaty area as well, while the Amaseno alluvium covered the remaining distance to the sea, impeding drainage of the Pontine graben along the way (Attema, 2017)

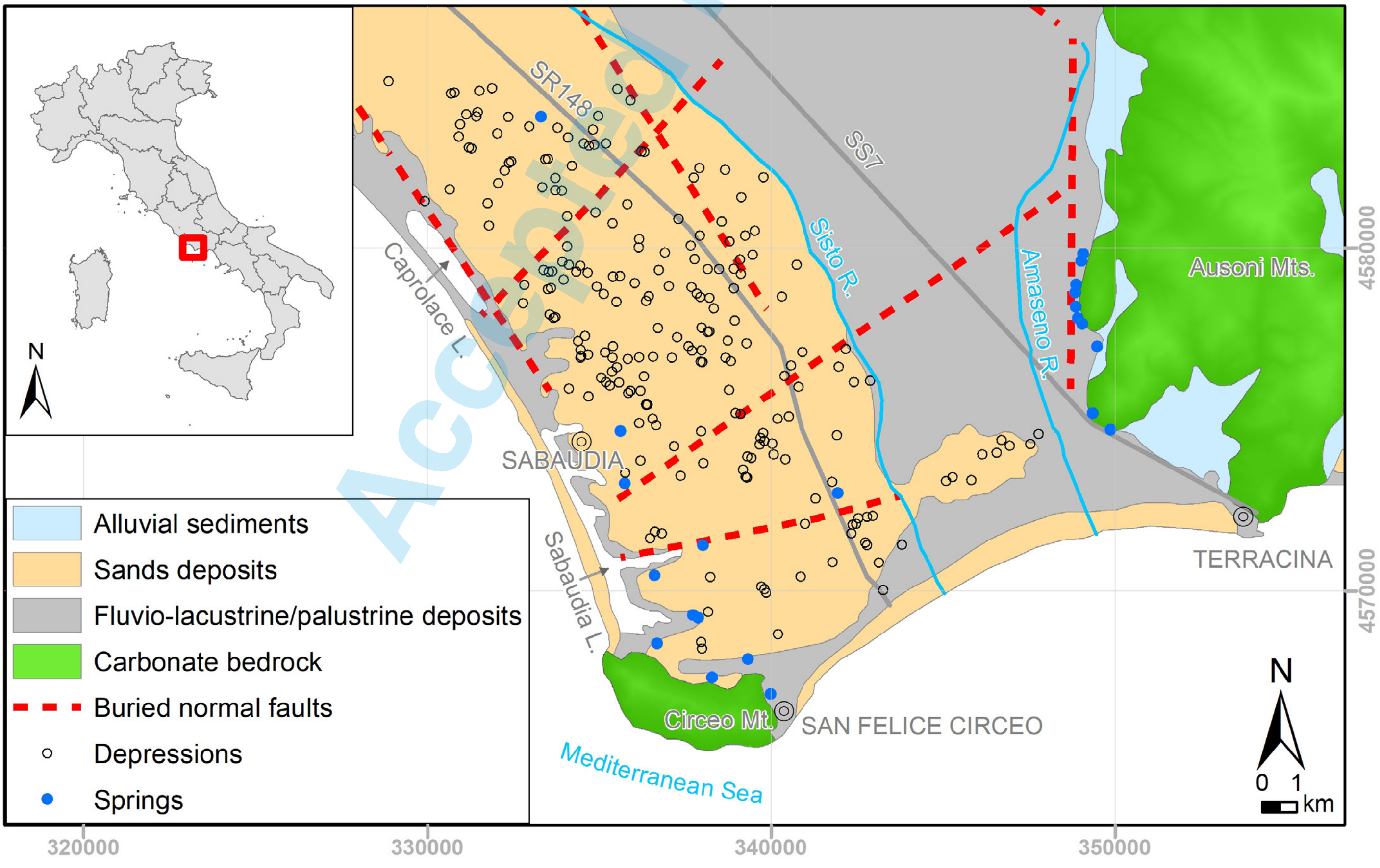

Fig. 1 - Geological map of the study area (modified after Capelli et al., 2012).

The southern sector of the Pontine Plain comprises a coastal lowland crossed by a dense network of artificial drainage canals, constructed between the 1920s and 1940s, to reclaim an extensive marshy area. Land reclamation resulted in profound transformations of the territory, both from a topographic perspective, through the removal of most pre-reclamation landforms, and from a socio-economic and environmental standpoint, with the development of intensive agricultural practices, the construction of transport infrastructure, and the establishment of new towns and rural settlements.

From a hydrogeological perspective, groundwater circulation within the Pontine Plain occurs at multiple levels and follows different flow regimes (Boni et al., 1980, 1986; Capelli et al., 2012; Gori et al., 2024). The Quaternary deposits host a shallow unconfined aquifer, beneath which a semi-confined aquifer extends, bounded at its base by Pleistocene clay deposits. In the piedmont sector of the plain, a confined artesian aquifer is also present within carbonate successions buried beneath the Quaternary deposits. This aquifer is hydraulically connected to the adjacent Lepini and Ausoni mountain structures and is confined at depths exceeding 100 m, with depths increasing toward the coastline (Clerici, 1924; Boni et al., 1980, 1986; Celico, 1983; Capelli et al., 2004; Petitta et al., 2006; Gori et al., 2024). The Plain hosts a major fault-controlled karst aquifer characterized by complex groundwater–rock interactions. A wide range of spring types, from cold karstic to sulfur-rich hypothermal waters, indicates mixing between Ca-HCO$_3$ groundwater from the northern Volsci Range karst aquifer and deep Na-Cl water that has interacted with Triassic evaporites (Anidriti di Burano Fm) at depths around 3 km. Travertine and alabaster concretions are found filling joints and fractures within the fault zone along the piedmont of the Pontina Plain. Fault systems act as preferential pathways for fluid and gas upwelling, with geochemical evidence pointing to interactions with deep evaporitic and magmatic sources and the involvement of mantle-derived CO$_2$ as a key driver of these processes (Gori et al., 2024). This indicates past fluid circulation through these structural features and that the present-day location of the springs results from prolonged interactions between climate and tectonics in the area and provide evidence of long-lasting fluid circulation and mixing within the fault-controlled karstic aquifer system. However, travertine deposits are not confined to the piedmont area but are distributed throughout the Pontine Plain, both at the surface and at depth, as evidenced by borehole data, where they are interbedded with Quaternary sediments. However, changes in fluid chemistry may promote the dissolution of continental carbonate rocks and, at a local scale, may contribute to the triggering of sinkhole processes. The geological and hydrogeological framework of the southern Pontine Plain suggests that endogenous gas emissions may contribute to the development of piping-related sinkholes (Almagià, 1904; Caramanna et al. 2004; Ciotoli et al. 2015; De Rossi, 1876; Di Filippo et al. 2012; Marinelli 1904; Nisio 2003, 2008; Meloni et al. 2013 a, b; Prony 1818). The study area is located at the margin between the Pontine coastal plain and the southwestern sector of the Alban Hills volcanic district, a region characterized by widespread degassing phenomena associated with deep magmatic and geothermal sources. Numerous historical and recent observations document episodic and diffuse emissions of CO$_2$-dominated gases, locally accompanied by H$_2$S and CH$_4$, particularly along structural discontinuities such as faults and fractures affecting the carbonate basement and its Quaternary cover (Gori et al., 2024). These gases migrate upward through preferential pathways and may accumulate temporarily within shallow, permeable sedimentary horizons, including sandy layers interbedded with clayey and peat-rich deposits. Several documented blowout events, triggered during drilling operations along the Tyrrhenian coastal plain, involved the sudden expulsion of gas together with water-saturated sands and silty–clayey materials, indicating the presence of overpressurized shallow systems (Aversa et al., 2016). From the Middle Ages to the nineteenth century, the Pontine territory was characterized by forests, woodlands, pastures, marshes, and a complex, poorly organized hydrographic network. Human communities inhabiting this area repeatedly attempted to mitigate these unfavorable environmental conditions through channelization, riverbed aggradation, deforestation, land clearance, and the burning of decomposed vegetal matter within marshy soils.

The Fascist-era bonifica integrale (Mussolini Law of 1928) led to a complete transformation of the hydrogeological and environmental components of the landscape (Martone, 2012, 2016), producing a territory characterized by intensive agricultural exploitation in which the original landscape identity (Fig. 2A) was entirely obliterated. This transformation resulted in the complete disappearance of the landforms addressed in the present study, namely the numerous sub-circular depressions documented in historical cartography since the seventeenth (Fig. 2B and Fig. 3), whose recognition is today possible only through indirect historical and geomorphological evidence.

MATERIALS AND METHODS

The study was based on the analysis of bibliographic, cartographic, and geognostic data to define the geological, geomorphological, hydrogeological, tectonic, and stratigraphic framework within which the depressions developed.

Pre-reclamation historical cartography was collected, specifically maps produced by the Istituto Geografico Militare (IGM) between 1926 and 1929 at a scale of 1:5,000.

The georeferencing of the IGM maps was carried out by Tecnostudi Ambiente S.r.l. on behalf of the Consorzio di Bonifica dell’Agro Pontino. The main operations performed, as reported in the accompanying documentation of the raster data, are summarized below: rasterization of the map (300 dpi resolution); acquisition of the geographic coordinates of the corners and their conversion into the UTM33 ED50 reference system (EPSG: 23033); georeferencing using the four corner points with the software TN-ShArc (Terranova) by applying a first-order polynomial function (Affine transformation). The mean error is not reported in the accompanying documentation.

The depressions identified in these maps were digitized, and their spatial distribution was analyzed to detect possible spatial patterns. A Kernel Density Analysis was performed using a GIS

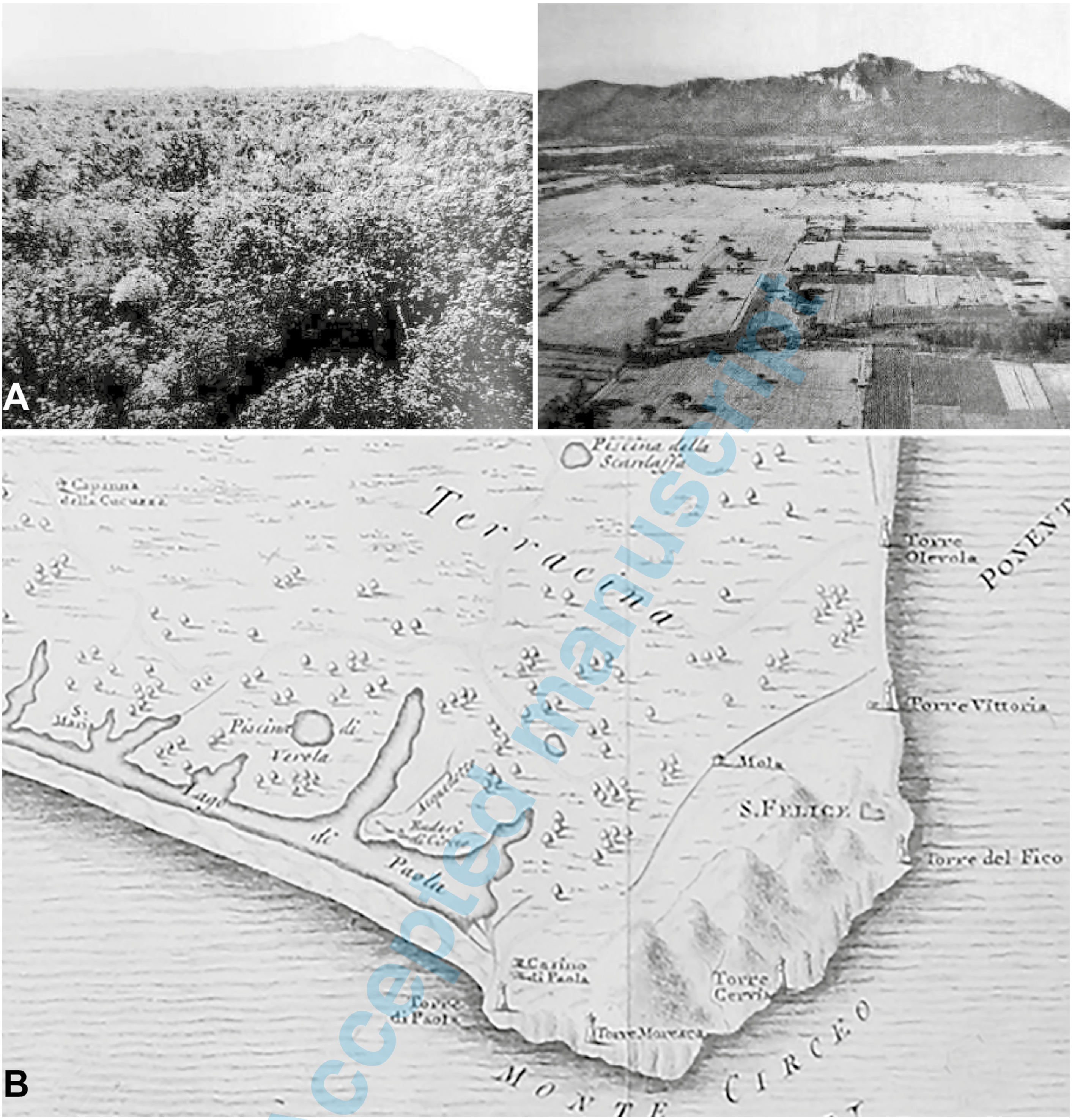

Fig. 2 - (A) Terracina before and after the land reclamation works (after Martone, 2012); (B) historical map depicting sub-circular depressional landforms, currently no longer preserved, in the study area (after Salvati, 1795).

environment (ArcGIS, ESRI). Centroids were extracted from each polygon, and the following parameters were used: 20 m output cell size, square meters area units, densities output values, no search radius specified (the algorithm automatically calculate a bandwidth based on the spatial configuration and density of input points). Four classes were identified using the Jenks/Natural Breaks algorithm, according to the following thresholds: <1.4; 1.4-2.4; 2.4-3.6; >3.6.

The sector east of the Sisto River, characterized by fluvio-lacustrine and marshy deposits, has been extensively investigated from a geotechnical perspective through analysis of borehole stratigraphy (Brunamonte & Serva, 1990; Brunamonte & Serangeli, 1996; Serva & Brunamonte, 2007). These data enabled determination of peat deposit thicknesses that locally exceed 30 m, inducing significant subsidence.

A similar analysis was conducted in the western sector of the study area by interpreting borehole stratigraphy from 110 drillings provided by ISPRA (Italian Database of shallow boreholes in compliance with the Governmental Law N. 464/84) and the

Fig. 3 - Excerpta from the 1693 Alessandrino Cadastre of the Pontine Plain, small sub-circular lakes are clearly recognizable and are most likely attributable to natural landforms, the so called “piscine” (A “Canale di Decima – Campo Bufalara” estate; C, D - “Gogna e Santo Appetito” estate).

Lazio Region, to determine the thickness of peat deposits. Spatial interpolation was performed using the Inverse Distance Weighting (IDW) algorithm (with following parameters, power: 5, search radius: variable, number of neighbors: 6 and output cell size: 20). This method was selected to obtain a localized, discontinuous distribution of peat thickness, consistent with the highly heterogeneous stratigraphic characteristics of the subsurface, characterized by strong vertical and lateral variability.

Figure 4A shows the location of the boreholes and the information layer representing peat thicknesses. The resulting distribution ranges from 0 to 6 m, with maximum values concentrated near the coastal lakes. However, relatively high thickness values are also observed in the inner sector of the analyzed area, in both its southern and northern portions. About the input stratigraphic data, boreholes indicating peat thicknesses of less than 1 m or reporting the presence of peat deposits at depths greater than 45 m below ground level were excluded from the interpolation, as they were not considered relevant to the potential genesis of shallow surface depressions.

Furthermore, a scarcity of stratigraphic data was identified in the central portion of the study area, encompassing Circeo National Park and a sector southeast of the park. For this reason, areas lacking stratigraphic information were excluded from subsequent statistical analyses using an analysis mask (shown in purple on the map). The mask also excludes coastal lake areas, where reliable assessment of the relationships between peat deposits and depressions requires additional, site-specific investigations, as discussed later.

In addition, based on currently available tectonic data (Capelli et al., 2012; Marra et al., 2021), a fault-density map of the study area was produced (Fig. 4B) using a Kernel Density approach. Finally, to explore potential relationships among the variables under consideration, zonal spatial statistics (Zonal Statistics) were applied. This method allows the calculation of statistical indicators for each zone defined by a “Zone Raster, based on the values of another dataset (“Value Raster”).

The zoning layer was derived from the raster representing depression density, which was reclassified into four classes (4 – very high, 3 – high, 2 – medium, 1 – low density) using the Natural Breaks classification algorithm. The “Value Rasters” used in the analysis were the datasets representing peat deposit thickness and fault density.

It is important to highligth that this statistical approach provides a decriptive comparison among the different classes hindering the possibility to identify the reason behind the association.

RESULTS

Approximately 300 depressions were identified and digitized from pre-reclamation cartography (Fig. 1). All depressions were digitized as polygon features by considering the toponyms (“Piscina . . .”), the cartographic features (“marsh” or “scarp” symbols) and the dimensions (exclusion of all depressions with an area smaller than 40 m^2).

The morphometric attributes, derived from the geometric analysis of the digitized polygons, are the following: surface areas ranging from about 40 m^2 to 130,000 m^2, maximum diameters between 8 m and 320 m, and estimated depths of 0.5–2 m.

The kernel density analysis results were summarized in two maps (Fig. 4), which illustrate the spatial overlay between

peat deposit thickness and depression density (A) and between fault density and depression density (B).

The results show a clear and consistent spatial association between depression density and peat thickness, with higher peat-thickness values systematically occurring in areas characterized by higher depression density.

The output of the zonal statistics analysis are summarized in Tables 1 and 2. Each record corresponds to a zone defined by the depression density raster (Zone Raster), for which several statistical parameters, namely count, minimum and maximum values, mean, standard deviation, and sum of pixel values, were calculated based on the cells of the corresponding Value Raster (peat deposit thickness and fault density) falling within each zone.

Regarding peat deposit thickness (Tab. 1), an increase in depression density (from Zone 1 to Zone 4) corresponds to a

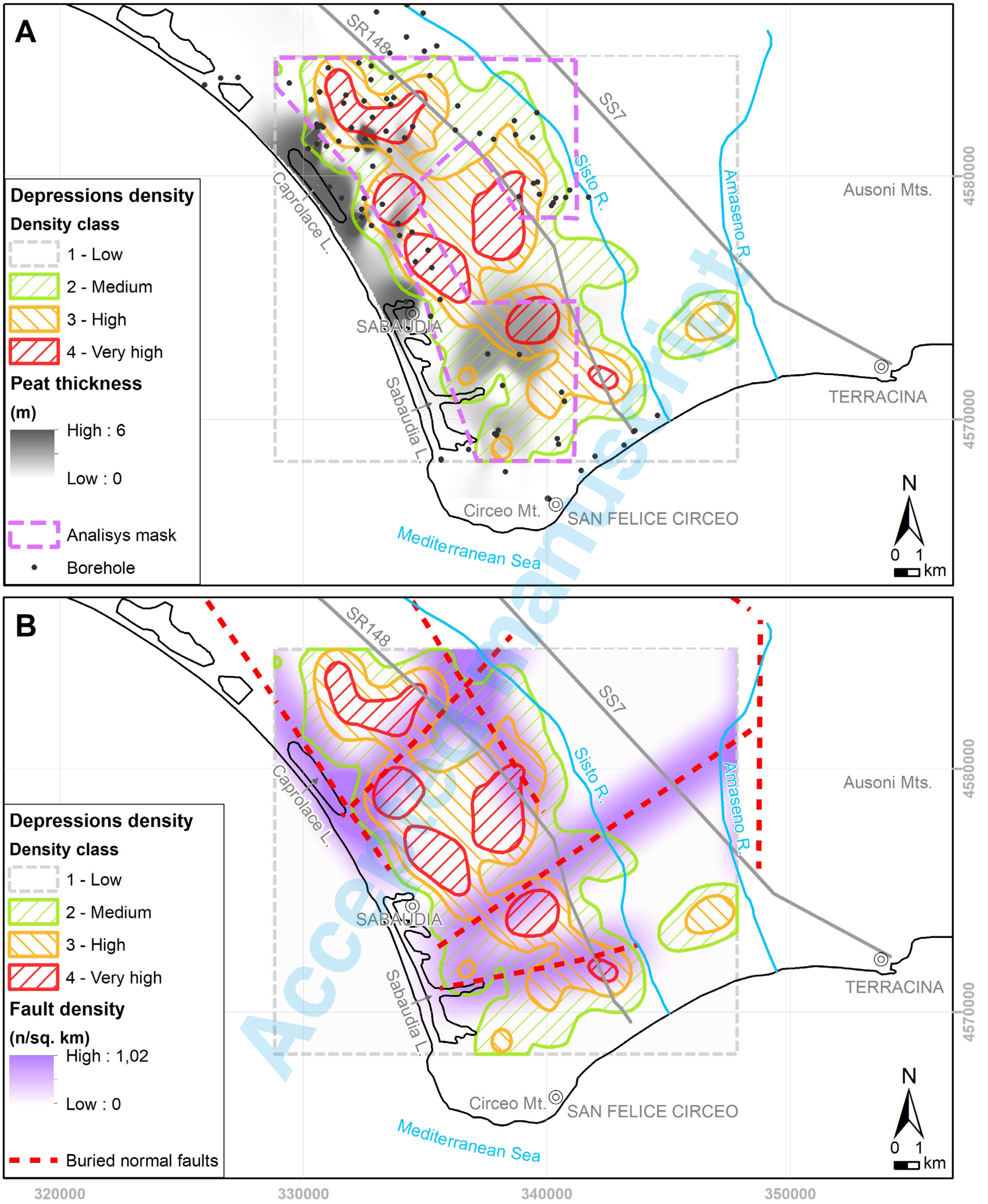

Fig. 4 - (A) Spatial overlay between peat deposit thickness and depression density; (B) spatial overlay between fault density and depression density (thresholds: <1.4; 1.4-2.4; 2.4-3.6; > 3.6 reclassified in Low – Medium – High – Very High).

Table 1

Depressions density class	N. of pixel	Area (m2)	Min (m)	Max (m)	Mean (m)	Std dev (m)	Sum (m)
LOW	4689	1875600	0	1,76	0,08	0,24	385,00
MEDIUM	10758	4303200	0	5,71	0,43	0,67	4603,93
HIGH	7616	3046400	0	6,00	0,55	0,85	4179,16
VERY HIGH	4630	1852000	0	5,98	0,56	0,85	2572,25

Table 2

Depressions density class	N. of pixel	Area (m2)	Min (n/sq. km)	Max (n/sq. km)	Mean (n/sq. km)	Std dev (n/sq. km)	Sum (n/sq. km)
LOW	354496	141798400	0	1,00	0,13	0,20	44876,41
MEDIUM	138833	55533200	0	1,02	0,30	0,23	41988,47
HIGH	108317	43326800	0	0,81	0,24	0,21	25470,68
VERY HIGH	59554	23821600	0	0,65	0,13	0,16	7883,14

progressive increase in the mean peat thickness (field "MEAN") within the zones. Mean values rise from approximately 0.08 m in the lowest-density zone to about 0.56 m in the highest-density zone, indicating a positive spatial association between peat thickness and depression density.

In contrast, the zonal statistics for fault density (Tab. 2) do not exhibit a comparable trend. Increasing depression density is not associated with a systematic increase in mean fault density, suggesting the absence of a clear spatial relationship between these variables at the scale of analysis.

The statistical approach adopted is limited to a descriptive comparison among the different classes and therefore does not allow clear relationships underlying the observed association to be established.

DISCUSSION

The spatial analysis indicates that surface depressions preferentially develop within sectors characterized by the outcropping of ancient coastal dune sands and that their distribution is not random but organized into distinct geographic patterns.

Among the variables investigated, peat deposit thickness exhibits the strongest spatial relationship with depression density, except within the coastal belt. This association suggests a potential genetic link between peat-rich stratigraphic levels and the development of shallow depressions, likely mediated by compaction processes affecting highly compressible sediments.

Peat collapse is a specific mode of shallow subsidence in peatlands, distinct from classic sinkhole formation. It is defined as a loss of strength and structural integrity in peat, leading to a decline in elevation (Flores, 2024). The collapse mechanisms include: degassing of pores (gases escape, promoting autocompaction); drainage of waterlogged peat (water loss leads to compaction); compaction of plant tissue (addition of labile carbon, oxygen, nutrients, and sulfate increases decomposition rates) (Nisio, 2003, 2008; Nisio et al., 2007; Caramanna et al., 2008).

In contrast, no clear relationship emerges between depression density and fault density. This may indicate limited direct tectonic control on the spatial distribution of the depressions, but the available fault dataset is characterized by relatively low resolution and significant interpretive uncertainty. Most mapped structures are buried and reconstructed indirectly, and their geometry is not always constrained by recent geognostic data. These limitations prevent a robust evaluation of possible cause–and–effect relationships between tectonic discontinuities and surface depressions.

However, in the southern Pontine Plain, the stratigraphic setting is particularly favorable for piping processes, as unconsolidated sands and organic-rich sediments overlie fine-grained, low-permeability layers. Gas ascent through these deposits may locally reduce effective stress, disturb sediment cohesion, and promote upward seepage of pore fluids. Repeated or sustained degassing could therefore enhance internal erosion, leading to the progressive removal of fine particles and the eventual collapse of the overlying material, consistent with a piping sinkhole mechanism.

Although subsidence related to peat compaction remains the dominant regional process affecting surface lowering (Brunamonte & Serangeli, 1996; Brunamonte et al., 2000; Serva & Brunamonte, 2007), the spatial association between gas emissions, mineralized springs, historical reports of "malaria-related" mephitic exhalations, and localized collapse phenomena suggests that gas-driven processes cannot be excluded, particularly in the southern sector of the plain north of the Circeo Promontory. The absence of systematic monitoring of gas fluxes and subsurface pressure conditions, however, currently limits a quantitative assessment of their role.

Overall, the available evidence supports the interpretation that endogenous gas upwelling may act as potentially significant triggering or predisposing factor for piping sinkhole development in the southern Pontine Plain, especially where structural pathways, high groundwater levels, and unconsolidated sediments coexist. Targeted geochemical surveys, continuous gas monitoring, and detailed subsurface investigations are required to better constrain this mechanism and its contribution to local geological hazard.

Based on the stratigraphic and hydrogeological setting, two main morphogenetic mechanisms can be considered. The first involves piping sinkhole processes, driven by upward flow of aggressive fluids along discontinuities, as suggested by the occurrence of travertine deposits and thermal springs in the area. The second mechanism involves subsidence related to peat compaction, supported by the spatial correspondence between peat thickness and depression density and by the widespread presence of compressible organic sediments beneath the dune sands.

The absence of depressions within the coastal lake sector may reflect either the limited lithostatic loading acting on peat deposits in lagoonal settings, or the occurrence of peat layers at depths insufficient to induce surface deformation. Discriminating between these alternatives requires additional subsurface data.

CONCLUSION

This study highlights that pre-reclamation surface depressions in the southern Pontine Plain are spatially concentrated within sectors dominated by ancient coastal dune sands and exhibit organized spatial patterns. A consistent spatial association is observed with peat deposit thickness, whereas no clear relationship is detected with fault density. Peat is very porous and can compress and “collapse” if any of the physical properties of the soil are compromised. Peat collapse results from the combined effects of drainage-induced water loss, gas degassing from pore spaces, compaction of soft plant tissues, and accelerated organic matter mineralization, leading to progressive pore-space reduction and surface subsidence. Piping sinkholes in successions dominated by clayey, sandy, or peaty sediments may develop through the upward migration of fluids and gases along discontinuities, which locally reduce effective stress, enhance internal erosion and particle removal, and ultimately lead to the collapse of the overlying deposits. Finally, the sedimentary succession filling the Pontine Plain graben includes interbedded layers of continental carbonate rocks (“travertines”), so the upwelling of chemically aggressive fluids could locally enhance the dissolution of these deposits and may locally contribute to sinkhole formation.

Based on the available data, a rather complex picture emerges that is not consistent with a single, univocal interpretation. Instead, it suggests that, despite the morphological convergence of the subcircular “Piscine” landforms, the mechanisms responsible for their genesis may differ and should therefore be evaluated on a case-by-case basis. Compaction of peat-rich sediments and related differential subsidence represent the most plausible mechanism controlling depression formation at the regional scale, but alternative processes, including piping sinkhole activity, as well as, at a more local scale, dissolution processes affecting continental carbonate rocks interbedded at multiple levels within the stratigraphic succession. cannot be excluded given current data limitations.

Future investigations should focus on acquiring high-resolution geognostic data, particularly through targeted boreholes near the depressions, and on developing an updated three-dimensional geological model of the subsurface. Such advances are essential for refining interpretations of the morphogenetic processes involved and for more precisely constraining the subsurface controls governing the evolution of these landforms in a reclaimed coastal lowland.

ACKNOWLEDGEMENTS

This work has been supported by European Union - NextGenerationEU - Mission 4 “Education and Research” - Component 2 “From Research to Business” – Investment 3.1 “Fund for the realization of an integrated system of research and innovation infrastructures” - Project IR0000037 - GeoSciences IR - CUP I53C22000800006.

The authors would like to thank the Lazio Region – Geological and Seismic Service, Geological and Seismic Assessments, Soil and Reservoirs Unit, for providing the pre-reclamation IGM topographic maps (1926–1929), which constituted a fundamental dataset for the development of this study.

The authors also thank Dr. Maurizio D’Orefice and Dr. Vittorio Chiessi for their valuable insights and constructive discussions, which significantly strengthened the interpretation of the results.

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