

Integrating archival data and remote sensing for the multi-temporal analysis of the Salse di Nirano (Italy) mud volcano field

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Abstract

Integrating heterogeneous historical and modern geospatial datasets provides an opportunity to extend the observation of active geological systems beyond the timespan covered by instrumental monitoring. This study applies this approach to the Salse di Nirano mud volcano field (Northern Apennines, Italy) to investigate its evolution over historical timescales. Historical cartographic and documentary materials, including an early twentieth-century technical report and other archival records, were reprocessed to reconstruct past surface configurations while explicitly considering scale limitations, spatial resolution and interpretative uncertainties. These historical datasets were independently evaluated and then compared with recent high-resolution products derived from Structure-from-Motion (SfM) photogrammetry and UAV-based magnetometric surveys, enabling a multi-temporal and multi-sensor characterization of surface morphology and shallow subsurface geophysical signals. The integrated analysis indicates a persistent large-scale spatial organization of the mud volcano system over more than a century, despite localized morphological evolution and substantial anthropogenic modification. Magnetic anomalies show only partial correspondence with surface morphology and, together with available geoelectrical and gravimetric information, support a structurally heterogeneous subsurface characterized by multiple preferential fluid-migration pathways rather than a single centralized conduit. Beyond the site-specific results, the study shows that historical datasets, although intrinsically less precise than modern surveys, can provide useful quantitative and semi-quantitative constraints when their internal consistency is independently assessed and their interpretation is restricted to an appropriate spatial scale. Their integration with modern remote-sensing and geophysical observations therefore provides a means to extend the observational window of slowly evolving geological systems. The proposed strategy represents a step toward a transferable multi-source workflow for investigating geomorphological and geophysical evolution over historical timescales, while explicitly accounting for the limitations and uncertainties associated with archival data.

Keywords: Salse di Nirano; Mud Volcano; Remote Sensing; Geomagnetism; Historical Data

1. Introduction

Mud volcanoes, locally known as “salse” in Italian, are geological features characterized by the emission of mud, water, and gases at the Earth’s surface. They are commonly associated with sedimentary basins and tectonically active regions, where overpressured fluids and gases, mainly methane, migrate upward through permeable pathways and crustal structural discontinuities. Although morphologically similar to magmatic volcanoes, mud volcanoes are not related to magmatic processes, but rather to the expulsion of fluids from overpressured sedimentary formations. Their development is controlled by a combination of sediment compaction, fluid overpressure, and tectonic stresses.

Because of their genetic link to subsurface processes, mud volcanoes are important indicators of fluid migration systems and crustal stress distribution, and their spatial distribution has been widely used to infer subsurface structural controls, particularly in tectonically active regions such as the Northern Apennines (Bonini, 2012). In addition, mud volcanoes represent significant natural sources of methane, with emissions ranging from localized seepage to large-scale fluxes comparable to anthropogenic sources. In Italy, they contribute substantially to regional hydrocarbon emissions, highlighting their relevance both for geological studies and for the global carbon cycle (Etiope et al., 2007).

The distribution and activity of mud volcanoes are strongly controlled by regional tectonic and structural settings. In the Northern Apennines, the geometry of the foreland monocline plays a key role in the structural evolution of the belt and in governing fluid migration within the crust (Mariotti and Doglioni, 2000; Capozzi and Piccotti, 2002). Lateral variations in monocline dip reflect inherited lithospheric heterogeneities and deep-seated discontinuities that influence the localization of surface geological features, including mud volcano systems.

The Northern Apennines are further characterized by lithospheric segmentation expressed by deep structural discontinuities, often interpreted as tear faults, which influence crustal deformation patterns and fluid circulation pathways within the orogenic system (Rosenbaum and Agostinetti, 2015). Within this framework, recent work (Vannoli et al., 2021) has proposed a classification of natural gas emissions in Italy into distinct “geofluid families” related to tectonic evolution. This model suggests that geofluid release is not random, but linked to long-lived lithospheric structures. In this context, CO₂-dominated emissions are mainly associated with extensional regimes, whereas mud volcanoes and hydrocarbon seeps are typical of compressional domains such as the outer Apennines and the Po Plain, where overpressured thermogenic gases preferentially migrate along structural discontinuities.

In the Northern Apennines, mud volcano fields are commonly located along major structural alignments, such as the Pedepenninic Thrust Front, where anticlines and transverse lineaments act as preferential pathways for fluid migration. These systems are generally interpreted as expressions of deep-seated, long-lived discontinuities that remain active across different tectonic regimes and may provide constraints on buried structural architectures relevant to seismic hazard assessment.

The Nirano mud volcano field represents a key natural laboratory for studying the structural control of mud volcano activity in the Northern Apennines. It is located near the intersection between the Pedepenninic Thrust Front and the Secchia Line, in proximity to a marked change in the foreland monocline geometry, suggesting the presence of deep-seated lithospheric discontinuities that may influence fluid migration pathways.

Historical observations and cartographic sources provide valuable constraints on the long-term evolution of the area. In particular, archival materials dating back to the late eighteenth century include historical scientific accounts, early twentieth-century reports and cartographic sources, with the work of Biasutti (1906-1907) providing the most detailed historical documentation of the site. Together with available twentieth-century orthophotos, these materials allow past surface configurations and activity patterns within the mud volcano field to be investigated over a temporal interval that cannot be covered by modern monitoring techniques. However, these sources are heterogeneous in quality and resolution, and their quantitative use requires careful evaluation of potential biases and uncertainties.

Recent advances in remote sensing techniques provide the opportunity to integrate this historical information with high-resolution geospatial datasets. UAV-based Structure-from-Motion (SfM) photogrammetry allows detailed reconstruction of the present-day morphology, while magnetometric measurements provide complementary information on shallow subsurface heterogeneities and structural discontinuities potentially related to fluid migration pathways. Their integration with historical evidence provides a means to investigate whether the spatial organization of surface activity has persisted through time and to explore its possible relationship with subsurface structural controls.

Despite the considerable geological and geophysical knowledge available for the Salse di Nirano, the integration of archival information with modern remote-sensing and geophysical datasets has so far been only partially explored at this site. Extending the observation window back through historical evidence can therefore help distinguish persistent spatial patterns from more recent morphological changes and provide a long-term reference for interpreting the evolution of the mud volcano field. In this context, the present study aims to (i) reconstruct the historical evolution of the Nirano mud volcano field using archival sources; (ii) characterize present-day morphology through high-resolution SfM data; and (iii) explore subsurface structural controls using magnetometric observations, with the overall objective of providing an integrated multi-source interpretation of mud volcano dynamics across multiple temporal scales.

2. Geological setting

The Nirano mud volcano field is located in the outer sector of the Northern Apennines, within the Po Plain foredeep of the Emilia-Romagna region (Italy) (Fig. 1a). This area marks the transition between the active compressional front of the Apennine fold-and-thrust belt and the undeformed foreland, developed within a flexural basin associated with Apennine orogenesis. The regional stratigraphy consists of a thick Mesozoic to Cenozoic sedimentary succession, including carbonates, marls, and clastic deposits, deformed within a NE-verging compressional regime active since the Neogene. The foreland monocline shows a progressive change in dip toward the Apennine chain, reflecting lithospheric flexure related to orogenic loading (Conti et al., 2020).

At the local scale, the study area is situated along the Pedepenninic Thrust Front (Fig. 1ab), a major structural boundary separating buried Apennine compressional structures from the relatively undeformed Po Plain. This setting is characterized by deep-seated faults and regional lineaments that influence both deformation patterns and fluid migration within the crust. In particular, transverse structures such as the Secchia Line intersect the main Apennine trend and are interpreted as lithospheric discontinuities that contribute to the complex structural architecture of the area and to the localization of mud volcano activity (Bonini, 2012; Vannoli et al., 2021).

The shallow subsurface is dominated by Quaternary alluvial and marine deposits, including the Plio-Pleistocene Argille Azzurre Formation (Fig. 1b), which provides low-permeability conditions favoring fluid overpressure and focused seepage (Revil, 2002). Recent geophysical investigations have further highlighted the complexity of the shallow subsurface beneath the Nirano field, identifying heterogeneous resistivity structures, fluid-rich domains and discontinuities potentially associated with preferential fluid migration pathways (Lupi et al., 2016; Romano et al., 2023). Recent studies also indicate that the spatial distribution of mud vents and gas emissions at Nirano is structurally controlled by fault and fracture networks acting as preferential pathways for fluid migration (Giambastiani et al., 2024; Nespole et al., 2024). Emission alignments predominantly follow NE-SW trends (Fig. 1c), suggesting the influence of transfer structures and strike-slip fault systems accommodating localized extensional deformation within the compressional Apennine belt.

Figure 1 summarizes the geological framework of the study area, including the regional geological context, the detailed structural setting and the surface distribution of active mud vents, which are organized along ridge and flat morphological domains controlled by the underlying structural architecture (Regione Emilia-Romagna, 2026).

3. Historical and archival data

Historical sources offer a means to extend the temporal framework of geomorphological analysis beyond the limits of systematic monitoring, enabling the reconstruction of past landscape configurations, early observational records and otherwise undocumented stages of environmental evolution. For mud volcano fields, this approach is particularly relevant for constraining long-term morphological variability and evolutionary trends.

For this study, archival research was conducted to collect historical documents, maps, and scientific descriptions related to the Salse di Nirano area. This survey identified several sources spanning the late eighteenth and nineteenth centuries, including the early scientific accounts of Lazzaro Spallanzani (1795), Giuseppe Bianconi (1840), and Antonio Stoppani (1876). These works provide historical descriptions and observations of mud volcano phenomena and their surface expression, documenting the early scientific knowledge of the Salse di Nirano and their surrounding landscape.

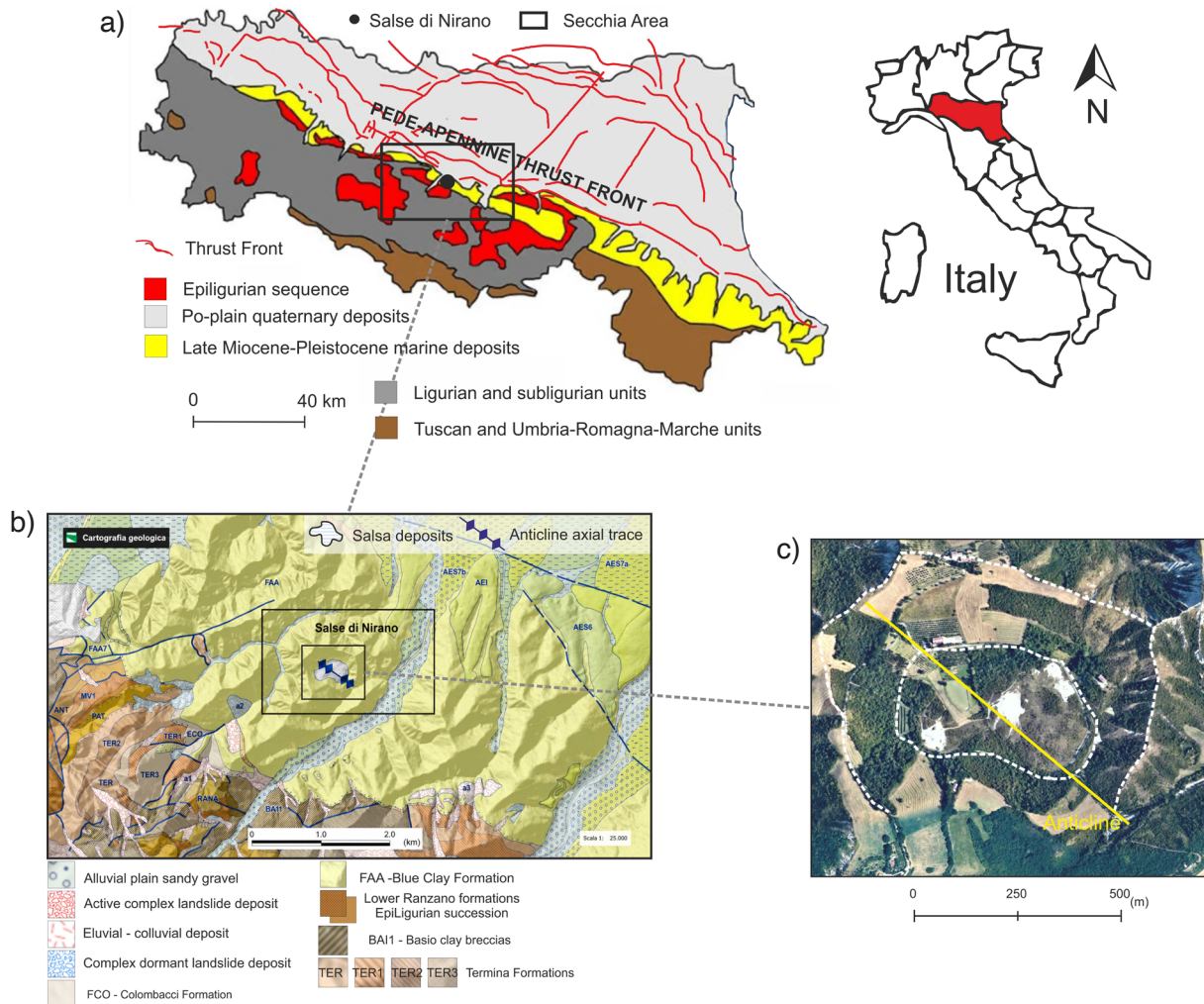


Figure 1. Geological and structural framework of the Nirano mud volcano field. (a) Regional structural and lithological map of the Emilia-Romagna Apennine margin (simplified after Bertolini, 2005), displaying the main tectonic structures (thrust fronts) and the location of the Secchia Area (black box) at the intersection with the Pedemontane Thrust Front; (b) Detailed geological map of Secchia Area and Nirano study area (scale 1:25,000) showing the local stratigraphic formations and landslide deposits; (c) Orthophoto of the Salse di Nirano field detailing the morphological boundaries of the active salsa deposits (dashed white lines) and the local anticline axial trace (yellow line).

Particular attention was given to the work of Renato Biasutti (1906-1907) and Giorgio Lorenzi (1902), whose descriptions, field observations, and cartographic materials provide more detailed information on the configuration of the Nirano area at the beginning of the twentieth century. These sources represent the most complete historical reference for evaluating long-term morphological changes and for comparing past and present conditions of the mud volcano field.

Figure 2 presents the frontispiece pages of the main historical sources used in this study, spanning from 1795 to 1906, documenting the original publications and providing the chronological and bibliographic framework for the archival dataset.

In the following sections, the work of Biasutti will be described in detail, with particular emphasis on his observations and cartographic contributions. Where relevant, additional information provided by other authors will also be considered and discussed in order to provide a more comprehensive historical framework of the study area.



Figure 2. Frontispiece pages of the historical publications and scientific reports used as primary sources. The chronological sequence includes seminal works by Spallanzani (1795), Bianconi (1840), Stoppani (1876), Lorenzi (1902), Biasutti (1906). These documents provide the historical descriptions and a few early cartographic data essential for the long-term morphological analysis of the site.

3.1 Biasutti report

The detailed study by Renato Biasutti (1906–1907) represents one of the earliest systematic analyses of the Salse di Nirano mud volcano field, combining descriptive observations, cartographic interpretation, and field measurements. The author provides a comprehensive account of the morphology, spatial organization, and activity of the mud volcano system, based on field surveys conducted between 1906 and 1907.

The Salse di Nirano are described as developing on the eastern slope of a hilly area composed predominantly of “Pliocene blue marls” by Biasutti, corresponding to the modern Argille Azzurre Formation, at an elevation of approximately 215 m a.s.l. The main morphological feature is a large circular depression, interpreted as a cirque-like structure, with a maximum diameter of about 800 m and steep inner slopes reaching an average height of 55 m. Within this depression, the mud emission area is organized into two main sectors, characterized by slightly different elevations and orientations and separated by a minor valley. The active mud emission area is estimated to extend over approximately 500 m in diameter and includes multiple vents organized into conical morphologies of variable height and slope.

Biasutti describes several mud cones with heights ranging from less than 1 m to more than 2.5 m, with the highest cones located near the margins of the cirque. Cone slopes vary significantly depending on their position and activity, with steeper slopes (up to 30°) observed in the larger cones and gentler slopes (6–10°) in flatter mud accumulations. The study also highlights the dynamic nature of the system, documenting variations in activity between the two surveys conducted in 1906 and 1907. Some vents show persistent activity, whereas others appear to activate or deactivate over time, with associated changes in mud consistency and emission intensity. The presence of drainage channels (“borratelli”) conveying mud flows downslope into the surrounding valleys is also described, indicating an active sediment transport system.

An important aspect of Biasutti’s work is the recognition of limited morphological changes through time, suggesting relative stability of the main structural and geomorphological features despite variations in eruptive activity. In addition, the author provides early insights into the presence of hydrocarbons in the subsurface, noting the occurrence of gas emissions and the broader regional context of hydrocarbon-rich formations. Finally, the report includes detailed references to previous literature and cartographic sources, highlighting the long-standing scientific interest in the Salse di Nirano and placing the study within a broader historical and regional research framework.

The most relevant quantitative information is represented by a topographic map derived from the “Tavoletta di Sassuolo”, which Biasutti significantly refined by providing a more detailed representation of the area. In addition, the author schematically depicted the active sector in the northeastern portion of the mud volcano field, offering a valuable reference for interpreting its morphological organization. The maps shown in Fig. 3 include the original captions and labels, preserving the historical context and providing direct insight into the author’s interpretation of the geomorphological features.

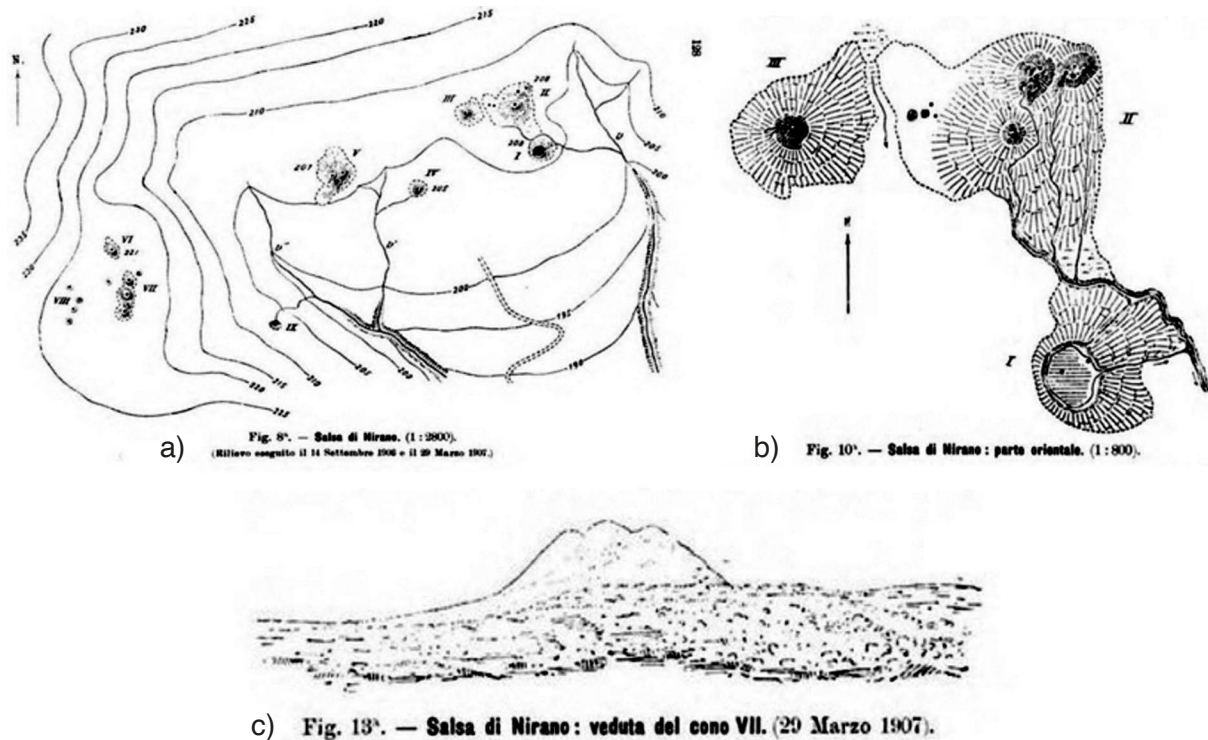


Figure 3. Historical cartography and landscape sketches by Renato Biasutti (1906-1907). (a) General topographic map of the Salse di Nirano area (scale 1:2800), which served as the baseline for the 1906 DEM reconstruction; (b) Detailed planimetry of the active eastern sector (scale 1:800); (c) Profile sketch of “Cono VII” in the western sector. These documents provide a precise record of the vent distribution and morphology at the beginning of the 20th century. Note that the original Italian descriptive captions from the historical publication are preserved within the figure.

3.2 Visual documentation

In addition to technical descriptions, maps and hand-drawn sketches, Biasutti also included photographic documentation of the Salse di Nirano area in his report. These historical photographs capture the landscape conditions of the early twentieth century and provide an additional qualitative reference for assessing long-term geomorphological changes.

The images depict a landscape that, despite differences in land cover and surface expression, retains a broadly consistent geomorphological framework. In particular, the surrounding slopes and badlands (“calanchi”) appear comparable to present-day conditions, whereas vegetation cover has increased significantly over time, partially obscuring surface details.

Despite their limited geometric precision and resolution, the overall morphology of the cirque-like depression allows meaningful qualitative comparison with the current landscape configuration. Figure 4 presents selected historical photographs approximately geolocated using modern orthophotos and satellite imagery (Google Earth), with reconstructed viewing directions enabling the identification of key geomorphological features and spatial relationships within the study area.

The value of Biasutti’s work lies in the availability of structured field descriptions, cartographic materials, and photographic documentation that allow direct comparison with present-day observations, providing a robust temporal reference for assessing long-term geomorphological changes in the Salse di Nirano area.

Earlier contributions, such as those by Antonio Stoppani (1876), include illustrative sketches of the mud volcano field that, although not geometrically accurate, preserve important qualitative information on the landscape configuration. These drawings highlight the presence of surrounding badlands (“calanchi”) morphologies, as well as a compartmentalized structure of the mud volcano field divided into a lower central-eastern sector and a higher western sector.

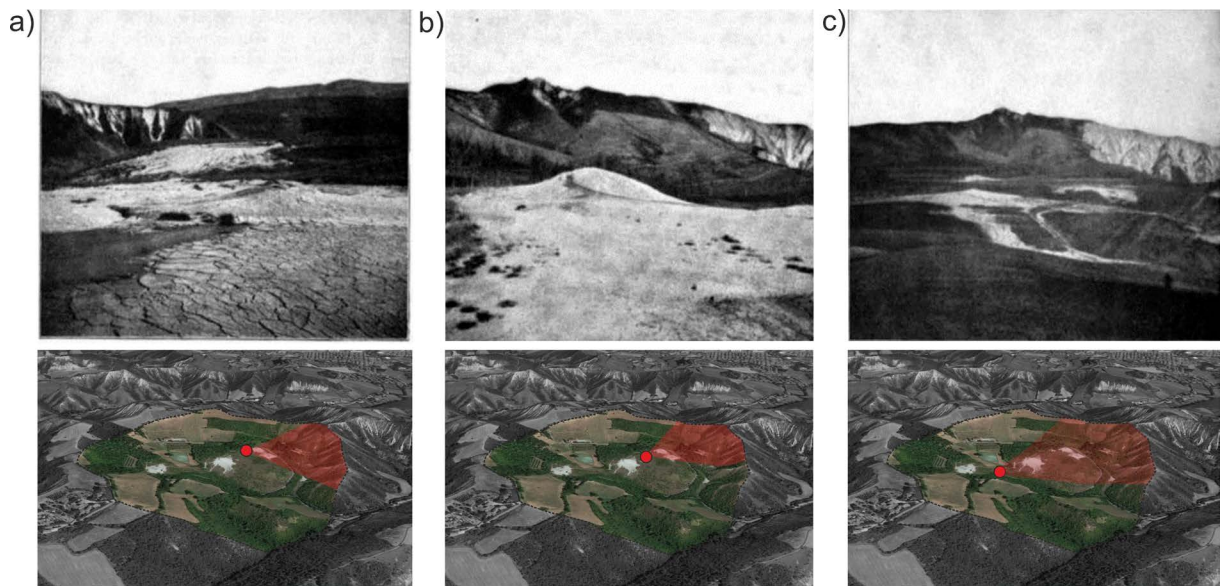


Figure 4. Historical photographs (1906) and modern viewpoint localization. Top: Original photographs by R. Biasutti. Bottom: Corresponding 3D satellite views (Google Earth), with red dots indicating the approximate observer locations and shaded sectors representing the reconstructed fields of view for: (a) northern sector looking southeast; (b) central area looking north-northeast; and (c) western sector looking east-northeast. These comparisons provide a qualitative visual reference for landscape evolution and geomorphological changes over more than a century.

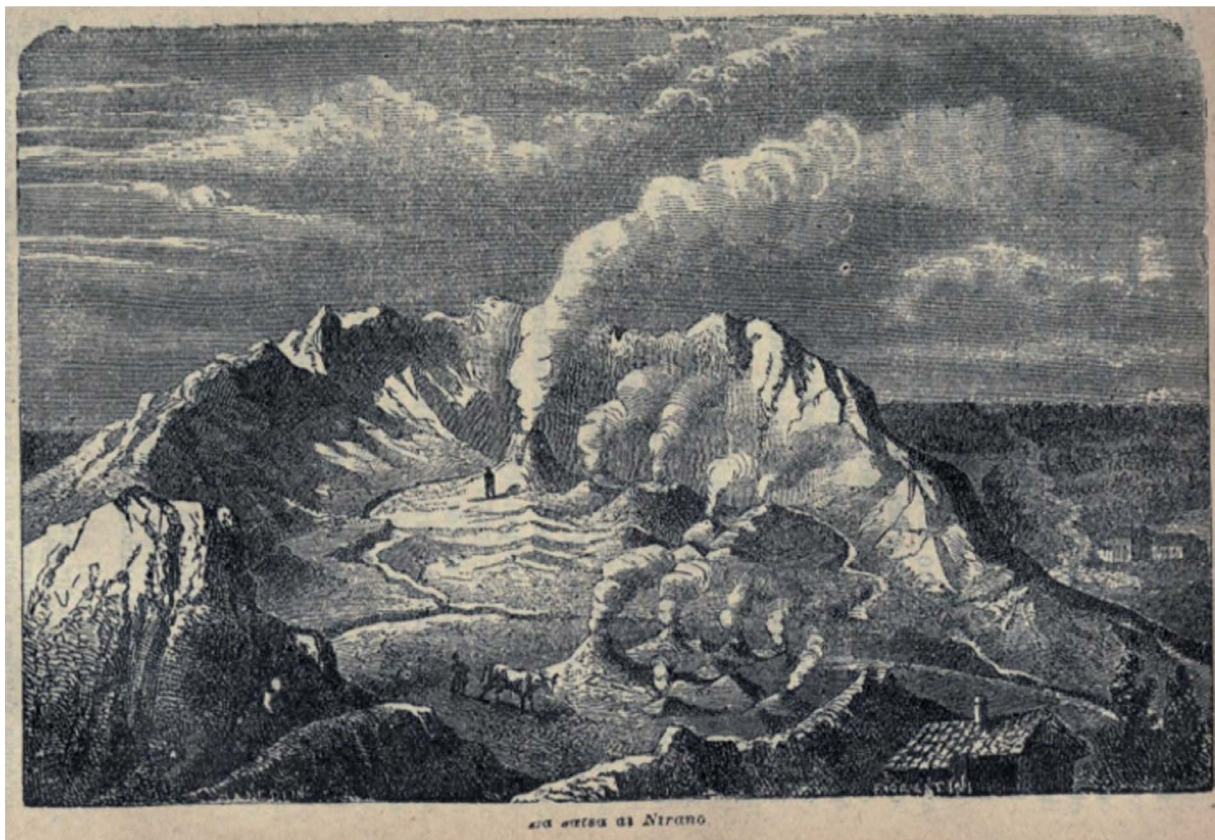


Figure 5. Historical illustration of the Salse di Nirano (Stoppani, 1876). This sketch provides an early geomorphological representation of the area, emphasizing the rugged badlands (“calanchi”) topography and the compartmentalization of the mud volcano field into distinct sectors. The drawing highlights the presence of active cones, drainage channels, and a central stream. The viewpoint is interpreted from the western elevated margin, looking east across the main depression.

The illustrations also depict schematic representations of mud emission activity and explicitly include human presence, such as agricultural activities and livestock, indicating the coexistence of natural processes and land use in the late nineteenth century. Figure 5 shows Stoppani's sketch, interpreted as a west-to-east perspective from the elevated western margin of the area. Despite its schematic nature, the drawing allows the identification of key geomorphological and hydrological features, including drainage channels and a central stream crossing the depression, supporting a qualitative reconstruction of the landscape at that time.

3.3 Historical cartography and data extraction

The original Biasutti (1906) map was constructed using the “Tavoletta di Sassuolo” as its primary cartographic reference and is reported with a nominal scale of 1:2800. However, the material available for this study consists of a printed reproduction of the map, which does not preserve a reliable metric reference, preventing the direct application of the reported scale.

To overcome this limitation, the original “Tavoletta di Sassuolo” was retrieved from the regional historical cartographic geoportal, where it is available in georeferenced form and already aligned with the modern Regional Technical Cartography (CTR). This provided a robust external reference for scale recovery.

The Biasutti map was then manually aligned with the corresponding section of the “Tavoletta di Sassuolo”, part of the official topographic cartography produced by the Italian Military Geographic Institute (IGM) in the early twentieth century, through visual matching of stable cartographic features and geomorphological boundaries.

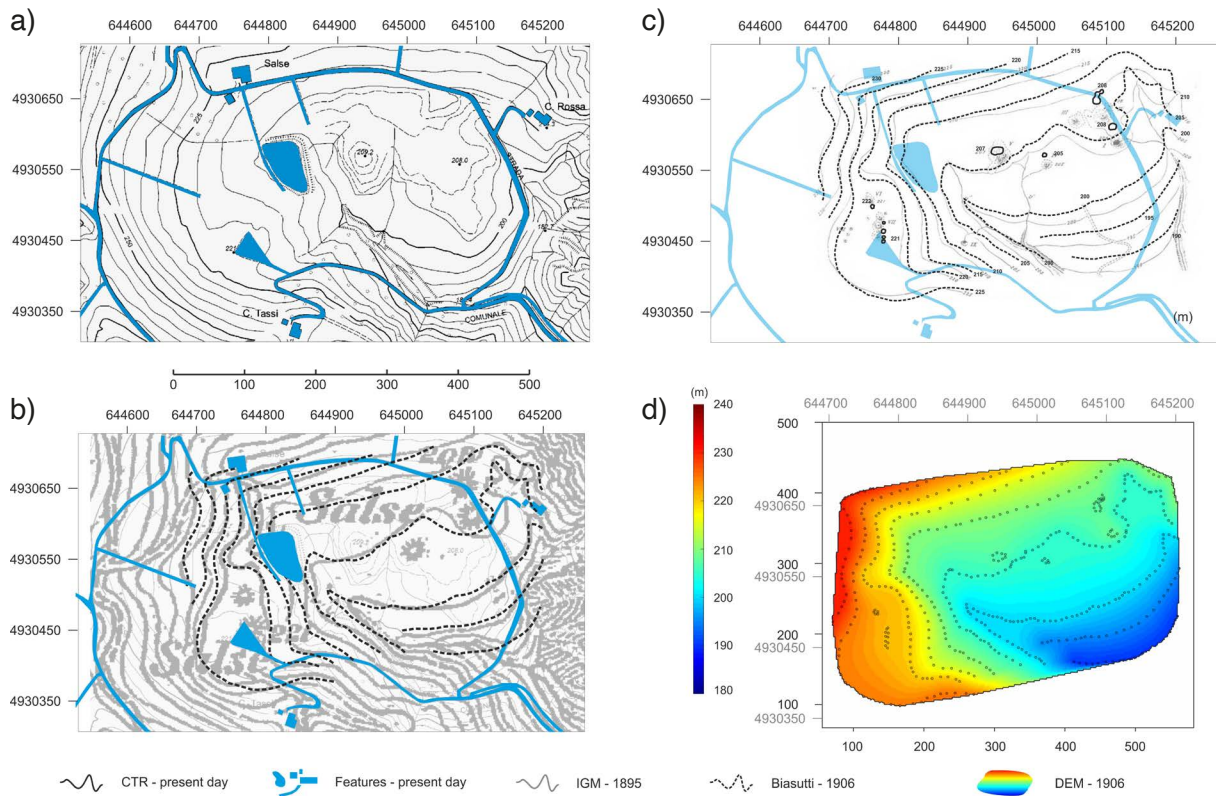


Figure 6. Workflow for historical cartographic integration and 1906 DEM reconstruction. (a) Georeferencing and alignment of historical IGM (1895) maps with current regional technical cartography (CTR); (b) scaling and rotation adjustment of Biasutti's 1906 map; (c) digitization process using DigMap software (Pesci and Randazzo, 2026), including contour extraction and point cloud conversion; (d) final reconstructed 1906 Digital Elevation Model (DEM). This workflow transforms qualitative historical records into a quantitative baseline for multi-temporal topographic analysis. Coordinates are reported in WGS84 / UTM zone 32N to improve spatial readability and facilitate comparison among panels; in panel (d), the coordinate grid is shown in light grey to avoid obscuring the relative elevation scale.

The consistency of the alignment was further verified against independent constraints reported in Biasutti’s descriptive account, including the approximate 500 m extent of the active mud volcano field and the ~38 m spacing between key vent alignments in the eastern sector. Additional checks against present-day topography confirmed the overall spatial coherence of the reconstructed geometry. While the original historical source inevitably retains some unresolved geometric uncertainties, the reconstruction shows a coherent overall spatial structure. Once the correct scale was established, the corrected map was processed using the custom digitization workflow proposed by Pesci and Randazzo (2026), enabling the extraction of contour lines and their conversion into a point-based dataset and subsequent digital elevation model (DEM). The workflow is also described in Fig. 6.

Finally, the application of the 1:2800 scale to the reconstructed geometry allowed an independent consistency check of the original cartographic sheet dimensions, yielding an estimated size of approximately 22×17 cm, consistent with standard early twentieth-century topographic map formats. This result further supports the validity of the scaling procedure and the internal coherence of the reconstructed dataset.

3.4 Data set consistency

An additional independent comparison can be made with the observations reported by Giorgio Lorenzi (1902), who focused on the eastern sector of the mud volcano field. Lorenzi documents a distance of approximately 38 m between northern vents and the adjacent southern aligned vents (corresponding to vents VI and VII in Biasutti’s map). These measurements are consistent with both the cartographic and descriptive information provided by Biasutti (1906) and the independently reported extent of the active mud volcano field (~500 m). Rather than providing exact numerical agreement, these converging values define a coherent order of magnitude across independent historical sources, supporting the robustness of the reconstructed spatial framework.

Table 1 synthesizes the main metric and cartographic constraints used in this study, including archival descriptions, historical cartography, and the derived digital elevation model (DEM). Together, these elements provide a consistent quantitative basis for the georeferencing and scaling procedure and allow comparison between historical and present-day topographic configurations.

Table 1. Metric and cartographic constraints derived from historical sources and used in this study. The table summarizes spatial information reported by Biasutti (1906) and Lorenzi (1902), as well as the geometric reference provided by the IGM “Tavoletta di Sassuolo”. These constraints were used to guide the scaling and georeferencing of the historical map and to ensure internal geometric consistency of the reconstructed dataset. The resulting framework provides a quantitative basis for multi-temporal comparison of topographic conditions in the Salse di Nirano area.

Source	Features	Description	Distance	Notes
Renato Biasutti (1906)	Overall active mud volcano field	Extent of the active salsa area	~500 m	Reported in the descriptive text; used as a primary spatial constraint for scaling
Renato Biasutti (1906)	Vent distribution (mapped features)	Distance between mapped structural elements (derived from map)	Variable (tens of meters)	Derived from cartographic interpretation and map scaling
Giorgio Lorenzi (1902)	Eastern active sector	Distance between northern vents and aligned southern vents (vents VI-VII in Biasutti map)	~38 m	Refers to the upper eastern part of the mud volcano field
Archival Cartography (IGM – Tavoletta di Sassuolo)	Base topographic reference	Cartographic framework used for Biasutti’s map	—	Used as the geometric reference for alignment and scaling
Present study (processed data)	Reconstructed DEM	Digital elevation model derived from historical map	—	Resolution limited, but suitable for comparative analysis

The use of historical cartographic sources provides a valuable opportunity to extract quantitative and spatial information from datasets predating systematic monitoring. However, several uncertainties must be acknowledged, arising both from the methodological workflow and from the intrinsic limitations of the historical materials. These include the original cartographic purpose and level of precision of the source material, the possible presence of interpretative elements derived from lower-resolution reference data, the limited spatial resolution of the historical map, and potential distortions introduced during surveying, reproduction, printing, or digitization. As a consequence, the reconstructed dataset is more suitable for identifying general spatial patterns than for resolving fine-scale topographic variability. Despite these limitations, it provides a coherent spatial framework broadly consistent with modern cartographic products (e.g., CTR), enabling meaningful comparison with present-day topography. The primary objective of this study is therefore not to reconstruct high-resolution geomorphological detail, but to analyse the spatial organization of mud volcano activity and its evolution over historical timescales. In this context, the relatively low-relief morphology of the Salse di Nirano system supports the use of vent-distribution patterns as a robust comparative proxy through time. Nevertheless, all interpretations should be considered in light of the inherent limitations of the historical dataset, which constrain the precision achievable in quantitative reconstructions.

4. Remote Sensing

Remote sensing techniques provide an effective framework for the analysis and monitoring of natural environments, enabling the acquisition of spatially continuous and multi-temporal datasets in a non-invasive manner. In geomorphological and environmental studies, these approaches support the interpretation of surface processes through the integration of optical, topographic, and geophysical information (e.g., Weng, 2012; Jensen, 2015). Over recent decades, the increasing availability of satellite, airborne, and terrestrial datasets has significantly expanded the potential of remote sensing applications. Optical imagery, digital elevation models, radar data, and laser-based surveys are now widely used for landform analysis, environmental monitoring, and the reconstruction of landscape evolution (e.g., Casu et al., 2006; Fisher et al., 2016).

In this study, remote sensing data are integrated with historical and cartographic sources to provide a modern reference framework for the interpretation of the Salse di Nirano system. The following sections describe the methodologies adopted, including photogrammetric reconstruction, multi-temporal comparison, and geophysical investigations.

Photogrammetry is a surveying technique dating back to the late nineteenth century, with its formal development in topographic mapping established in the early twentieth century (Remondino and El-Hakim, 2006). In recent decades, it has undergone substantial advances with the introduction of Structure-from-Motion (SfM) techniques, which have significantly transformed image-based 3D reconstruction workflows (Snively et al., 2008; Schönberger and Frahm, 2016).

SfM photogrammetry enables the reconstruction of three-dimensional geometry from overlapping images without requiring pre-calibrated camera networks. It relies on automated feature detection and matching to identify homologous points across multiple images, which are then used to estimate camera positions and scene structure within a unified reference system.

The reconstruction process is based on bundle adjustment, a non-linear optimization procedure that minimizes reprojection error and allows simultaneous refinement of internal and external camera parameters. Once a sparse model is obtained, dense reconstruction is achieved through multi-view stereo (MVS) algorithms, which increase point density by establishing additional image correspondences (Furukawa and Ponce, 2010). The resulting point cloud can be processed into digital surface models (DSM) or digital elevation models (DEM), depending on the removal of non-ground elements such as vegetation or anthropogenic structures.

Here, SfM photogrammetry is used to process modern Unmanned Aerial Vehicle (UAV) imagery and generate high-resolution three-dimensional spatial datasets, which provide the present-day reference for comparison with historical cartographic reconstructions and other archival sources (Westoby et al., 2012).

UAVs, commonly referred to as drones, have become widely used platforms for remote sensing applications, providing a flexible solution between ground-based surveys and conventional airborne or satellite observations. Their ability to acquire very high-resolution imagery at low altitudes makes them particularly suitable for detailed geomorphological and environmental analyses. Modern UAV platforms are commonly equipped with high-precision GNSS systems and increasingly integrate Real-Time Kinematic (RTK) or Post-Processed Kinematic (PPK) correction

strategies. These technologies improve absolute georeferencing accuracy and reduce dependence on dense ground control networks while maintaining high metric consistency (Cledat et al., 2020; Štroner et al., 2021; Žabota and Kobal, 2021).

UAV-based photogrammetry has demonstrated strong applicability in geomorphology, archaeology, and volcanology, particularly for the reconstruction and monitoring of surface morphology in complex or hazardous environments (Manfreda et al., 2018; Forte and Campana, 2021; James and Robson, 2012; James et al., 2019), including the monitoring of active mud volcanoes in Italy (Brighenti et al., 2021).

In this study, UAV surveys were conducted using a DJI Matrice 350 RTK platform equipped with a Zenmuse P1 camera. The acquired multitemporal RGB datasets were processed using SfM and MVS workflows to generate high-resolution DSM/DTM products, subsequently used for morphological analysis and multi-temporal comparison with historical cartographic and archival datasets.

4.1 Photogrammetric Surveying

In 2022, the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italian National Institute of Geophysics and Volcanology) funded the ProMud project within the Pianeta Dinamico program, aimed at developing standardized multidisciplinary workflows for the study and monitoring of Italian mud volcano systems. Within this framework, UAV photogrammetric surveys were carried out at selected mud volcano sites in the Emilia-Romagna Apennines, including the Salse di Nirano field, to generate high-resolution topographic datasets suitable for geomorphological analysis and multi-temporal comparison.

The main UAV acquisitions were performed between November 2024 and March 2026, resulting in a multitemporal dataset composed of dense point clouds, surface models, and orthophotos. Surveys were conducted using a DJI Matrice 350 RTK platform following a consistent acquisition geometry across all campaigns. Each survey consisted of approximately 235 images acquired at an average flight altitude of ~80 m AGL (Above Ground Level), with a grid-based flight plan and 70-80% image overlap. The resulting dataset covers an area of approximately 0.17 km², with an estimated ground sampling distance (GSD) of ~3 cm/pixel, providing a high-resolution basis for geomorphological analysis and multitemporal comparison.

Photogrammetric processing was carried out in Agisoft Metashape Professional (v. 1.7.5) following a standard Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflow, in accordance with established procedures for UAV-based SfM processing and geometric error mitigation (James et al., 2017). Image alignment achieved full camera registration within the WGS84 reference system, with a mean reprojection error of ~0.13 pixels and an average tie point multiplicity of 4.46, indicating a stable photogrammetric solution.

Dense image matching produced a point cloud of approximately 9.7×10^7 points. The final 3D reconstruction includes a mesh model exceeding 8.4 million faces and 4.2 million vertices, supporting detailed representation of surface morphology.

Final products include a textured 3D model, a digital elevation model (DEM), and a high-resolution orthomosaic with a raster size of approximately 50k × 40k pixels. The DEM provides a consistent terrain representation at decimetric resolution, suitable for geomorphological interpretation and comparison with historical cartographic datasets.

Overall, the processing workflow proved computationally efficient, with image alignment completed in less than one minute and dense reconstruction in a few minutes on a workstation equipped with an Intel i7-11800H CPU, 32 GB RAM, and an NVIDIA RTX 3080 GPU. Figure 7 illustrates the quality assessment and results of the UAV survey, including image overlap distribution, camera network geometry, and the final orthomosaic integrated with the DEM.

4.2 Magnetometric Surveying

The geomagnetic survey is based on the measurement of spatial variations in the Earth's magnetic field, which is locally perturbed by variations in the magnetic susceptibility of subsurface materials. Ferromagnetic minerals, lithological contrasts, and buried structures can generate measurable anomalies in total magnetic field intensity, providing useful constraints on shallow subsurface properties (Blakely, 1995; Campbell, 2003).

In recent decades, geomagnetic prospecting has become a well-established near-surface geophysical method, widely applied in geological, environmental, and engineering investigations. UAV-borne magnetometry has further

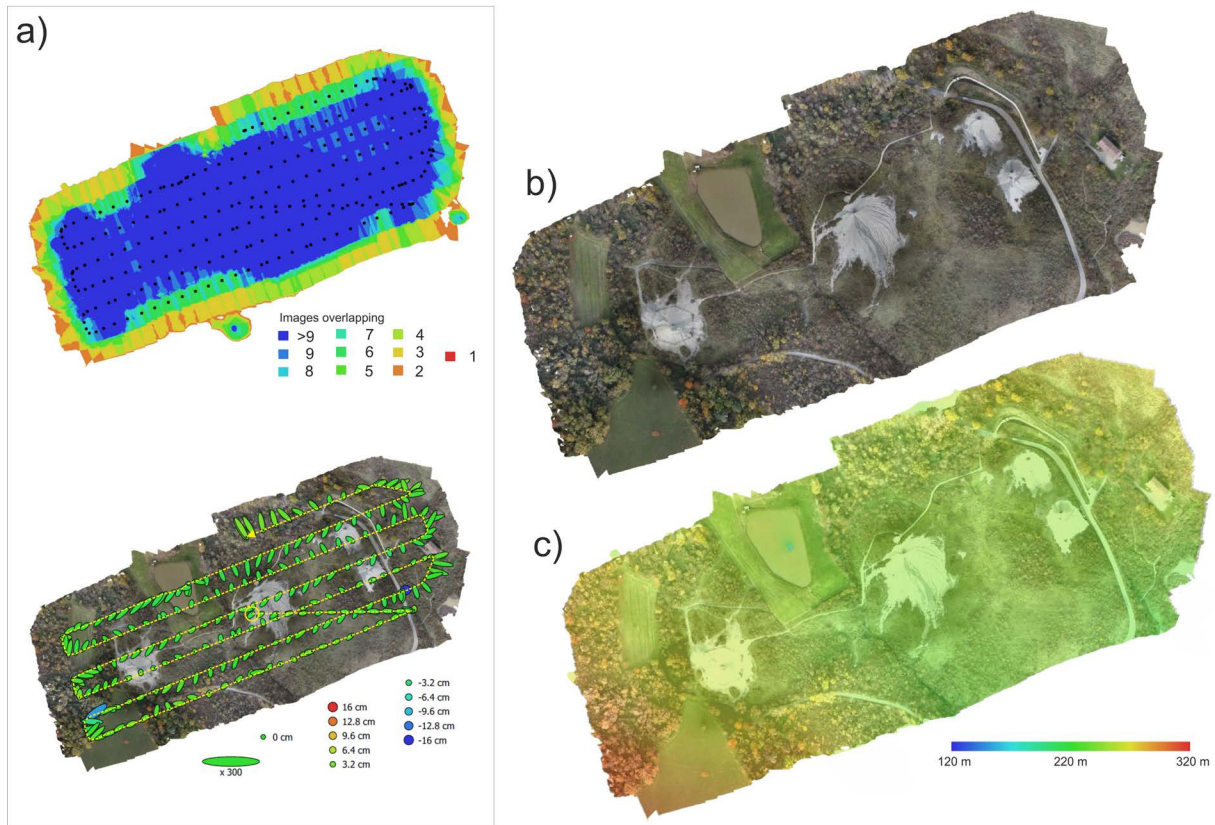


Figure 7. SfM photogrammetric survey processing and quality assessment. (a) Quality control maps showing the number of overlapping images per pixel (top) and the camera locations with associated positional error ellipses (bottom). The high overlap (>9 images) and low error distribution confirm the reliability of the reconstructed geometry. (b) Final high-resolution orthomosaic of the study area (top) and (c) its integration with a semi-transparent Digital Elevation Model (DEM) (bottom), with elevations ranging from 120 to 320 m.

improved spatial resolution and operational efficiency, enabling dense and systematic acquisition of magnetic data over complex terrain (Pesci et al., 2026; Sapia et al., 2025; Cunningham et al., 2018).

Despite these advances, magnetic interpretation requires careful consideration of external and instrumental effects, including diurnal field variations, flight altitude fluctuations, sensor stability, and electromagnetic interference. For this reason, magnetic data are most effectively interpreted when integrated with independent datasets such as photogrammetric models and geological observations.

In this study, UAV-based magnetic surveys were conducted using a DJI Matrice 300 platform equipped with a QTFM optically pumped rubidium vapor magnetometer (QuSpin). The sensor was mounted on a towed, aerodynamically stabilized “bird” system suspended approximately 10 m below the UAV to reduce electromagnetic noise induced by onboard electronics and propulsion systems. The sensor exhibits a sensitivity better than $3 \text{ pT}/\sqrt{\text{Hz}}$ and a sampling rate up to 1000 Hz, making it suitable for high-resolution UAV applications. Additional details on the system configuration developed at the INGV laboratory are provided in Pesci et al. (2026).

Surveys were flown at an average altitude of ~ 90 m AGL following predefined linear flight paths, ensuring systematic coverage of the study area. Magnetic measurements were continuously recorded along flight trajectories with an average spatial sampling interval of approximately 5 m and directly georeferenced using onboard GNSS positioning.

Given the spatial resolution of the dataset and GNSS-related uncertainties, no explicit temporal synchronization with optical acquisitions was required. At this scale, minor timing offsets are negligible with respect to the sampling interval and do not affect the spatial interpretation of magnetic anomalies.

The resulting dataset consists of a spatially continuous magnetic anomaly dataset directly comparable with UAV flight trajectories and photogrammetric products. Figure 8 summarizes the magnetometric survey configuration, sensor setup, and acquisition geometry.

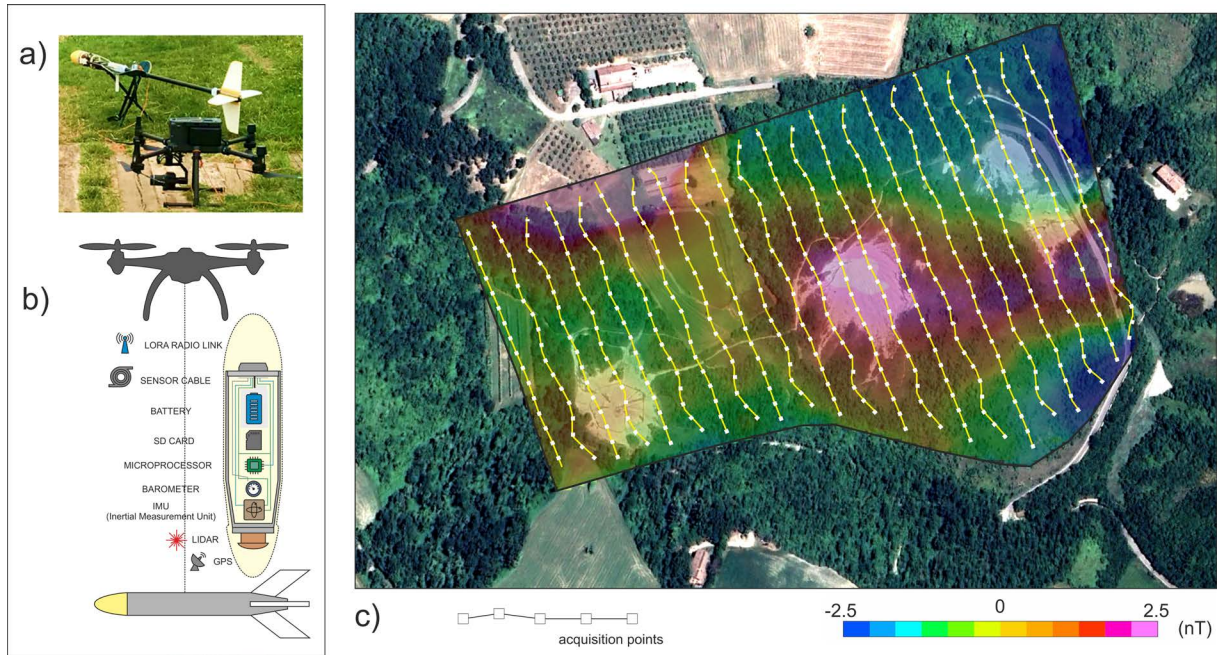


Figure 8. UAV-borne geomagnetic survey: setup, acquisition, and anomaly mapping. (a) The UAV platform equipped with the suspended “bird” magnetometer system during field operations. (b) Internal schematic of the sensor system, highlighting the integrated components (LiDAR, IMU, GPS, and data processing unit). (c) Residual magnetic anomaly map (nT) overlaid on the study area with the drone flight paths (yellow lines) illustrating the high-density spatial coverage.

5. Data Analysis

Up to this point, the different datasets used in this study have been presented individually. Historical cartographic sources provide a refined representation of the study area, improving late 19th-century mapping and adding valuable morphometric information. From the georeferenced historical map, a derived DEM was generated. Although this product is affected by intrinsic limitations related to contour spacing (5 m interval) and digitization procedures, it provides a consistent large-scale baseline for comparison with modern datasets.

UAV-based photogrammetry provides a high-resolution, up-to-date digital elevation model of the Salse di Nirano area, including active emission zones and surrounding terrain, capturing the current morphological configuration with decimetric detail. The geomagnetic survey adds a complementary geophysical layer, providing a spatially aligned magnetic anomaly map co-registered with the SfM-derived model. Variations in magnetic intensity may indirectly reflect subsurface heterogeneities such as fractures or lithological contrasts. Together, these datasets form a multi-source framework for analysing both surface morphology and subsurface structure across different temporal scales.

5.1 Multi-temporal topographic Differences

This subsection focuses on the comparison between past and present surface conditions of the Salse di Nirano area, with the aim of identifying and quantifying morphological changes over time. The analysis is based on the comparison between the UAV-derived SfM point cloud and the historical surface model reconstructed from georeferenced cartographic sources.

The two datasets, representing different temporal stages, were co-registered within a common reference framework using PolyWorks (InnovMetric) and analysed through a cloud-to-cloud comparison workflow. This represents the workflow adopted in this study, although other alignment methods or software may be used depending on the operator's choice and available tools, provided that they allow minimization of differences between the compared datasets.

Figure 9 highlights the main variations between the 2025 UAV model and the 1906 reconstructed surface. Several anthropogenic modifications are immediately evident, including the construction of a road crossing the eastern sector, the creation of an artificial pond in the north-western area, and the installation of a pedestrian network that now regulates access to the site. A general expansion of vegetated areas, including woodland and cultivated zones, is also observed.

In less anthropogenically modified sectors, more subtle geomorphological changes emerge. Positive elevation anomalies in the south-eastern sector may be associated with sediment accumulation processes, while similar trends in the northern sector likely reflect vegetation growth.

The north-eastern sector, hosting the main mud volcano structures, shows two relevant features: (i) an overall increase in elevation of the main cones and emission structures, and (ii) the persistence of a well-defined depression between the two main emission centres, previously identified by Biasutti as structures I and II.

The central sector of the area shows clear vertical development, indicating an increase in elevation relative to its historical configuration. The most significant changes occur in the western sector, where the 1906 map indicates small aligned structures on a low-relief surface, whereas the present-day morphology is characterised by a more pronounced conical geometry and increased topographic relief.

The channel separating the two main sectors, responsible for the drainage of mud and runoff, appears more deeply incised in the modern model, suggesting ongoing erosional and mass-wasting processes.

Overall, the comparison indicates relative stability of the emission areas in the central and eastern sectors, while the western sector exhibits the most pronounced morphological evolution, likely driven by combined erosional, gravitational, and surface reworking processes. These changes are particularly evident in areas with higher topographic gradients.

It is important to note that, although the analysis is based on quantitative procedures, it relies on datasets with different resolutions and intrinsic uncertainties. Therefore, the results should be interpreted as a combination of quantitative and semi-quantitative evidence, bridging strict metric comparison and geomorphological interpretation (James et al., 2019).

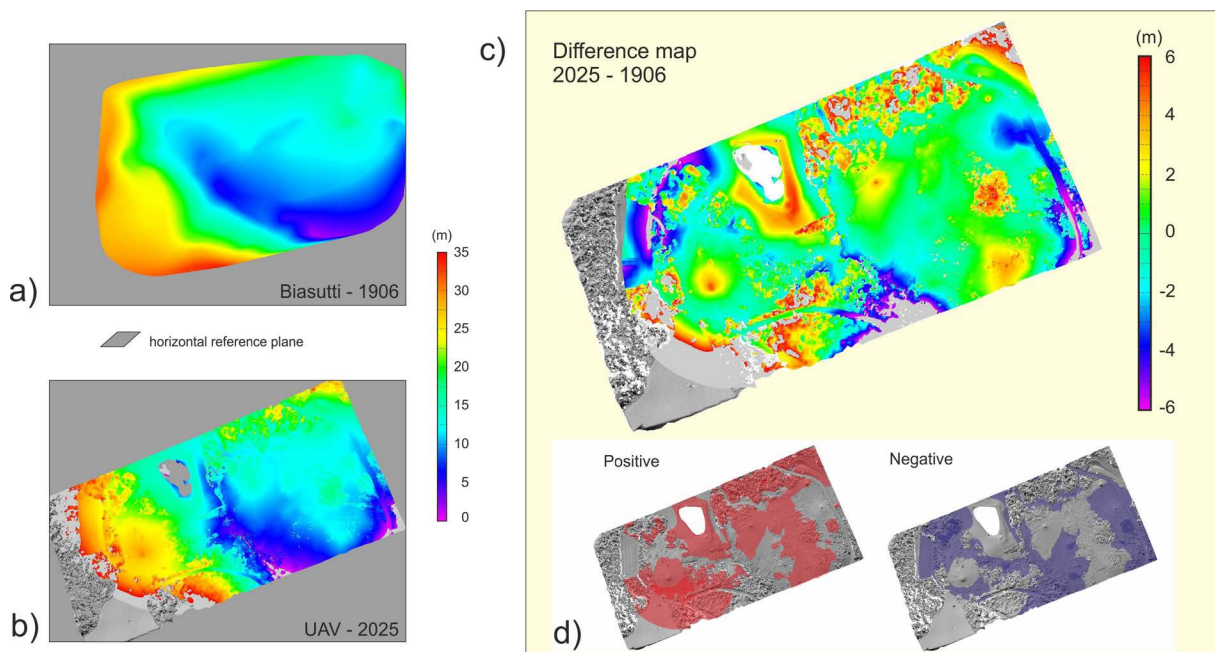


Figure 9. Multi-temporal morphometric analysis and topographic change detection (1906-2025). (a) Digital Elevation Models (DEMs) derived from the 1906 historical map (top) and (b) the 2025 UAV photogrammetric survey (bottom). Elevation values are calculated as the distance from a common horizontal reference plane passing through the lowest point. (c) Topographic evolution over 119 years. The Difference map (2025-1906) (top) quantifies elevation gain (red/yellow) and loss (blue/purple) in meters. (d) The lower sub-panels isolate the spatial distribution of Positive and Negative variations, respectively, to emphasize areas of net accumulation or subsidence/erosion.

5.2 Geomagnetic anomalies

The geomagnetic data acquired over the study area were projected onto the UAV-derived orthophoto to provide a spatially consistent framework for comparing magnetic anomalies with surface morphology. This allows a first-order qualitative assessment of the relationship between magnetic signal distribution and geomorphological features.

The magnetic field exhibits a structured spatial pattern that does not directly follow the morphology of the mud volcano edifices. Magnetic isolines cross the Salse di Nirano field with geometries only partially consistent with surface structures (Fig. 10). A main alignment of positive anomalies extends eastward from the central sector, with a slight northward curvature. Additional positive anomalies are present in the northern area, although with limited spatial continuity.

Lower positive values are observed in the western sector, partly corresponding to older or less active morphological features, while the north-eastern and south-eastern sectors are predominantly characterized by relative negative anomalies.

To assess the potential contribution of topography to the observed signal, a simplified forward modelling approach was applied using the UAV-derived DEM. The terrain was discretized into elementary prisms, each assigned a uniform magnetization aligned with the present geomagnetic field direction (Blakely, 1995; Nagy et al., 2000; Ishihara, 1979).

The resulting synthetic field was normalized and used solely to evaluate spatial patterns, as no direct constraints on subsurface magnetization were available. Comparison between the synthetic topography-induced field and the measured magnetic anomalies indicates only partial correspondence at local scale (Fig. 10). In particular, the geometry and polarity of the main magnetic features are not reproduced by the synthetic model, suggesting that subsurface sources dominate the observed signal. This simplified modelling therefore supports a qualitative interpretation in which topographic effects represent a secondary contribution, providing a reference framework rather than a controlling factor in the observed magnetic field distribution.

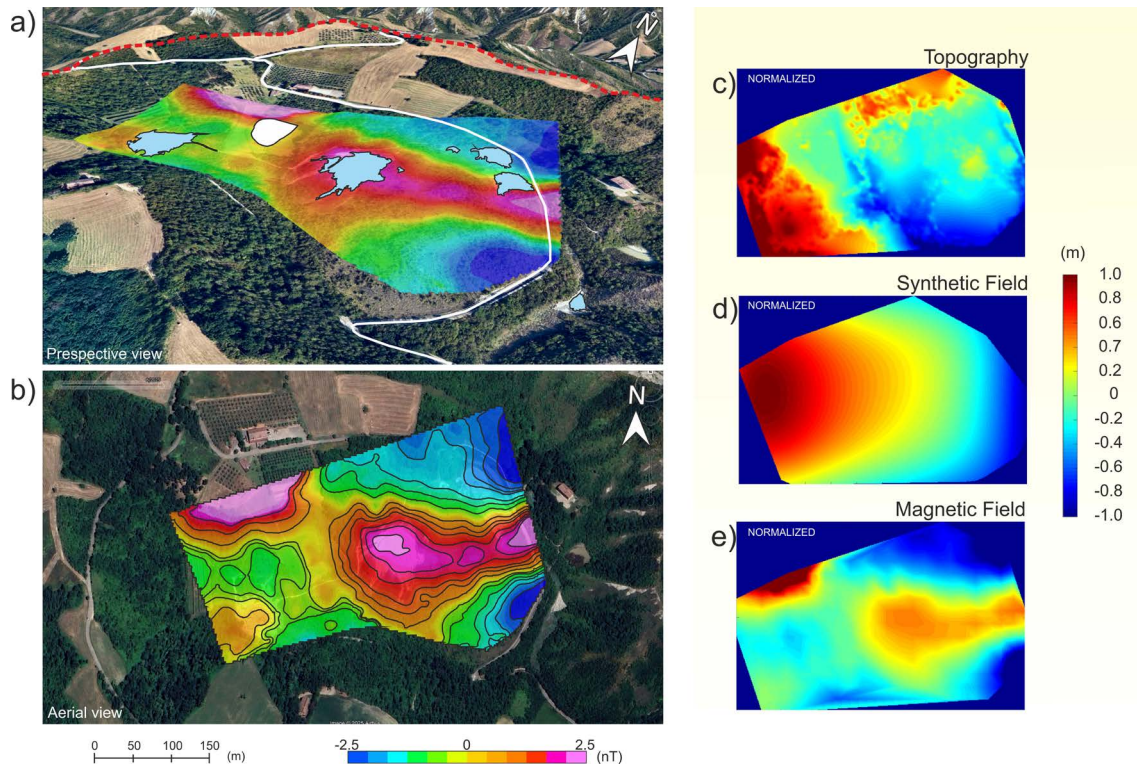


Figure 10. Geomagnetic field distribution over the Salse di Nirano area. (a,b) Perspective and aerial view showing the residual magnetic anomaly (nT) overlaid on the terrain. Main emission features and mud flows are outlined and highlighted in light blue. A red dashed line indicates a morphological ridge. (c,d,e) Normalized comparison maps (-1.0 to 1.0) showing Topography, Synthetic Field (topography-induced) and measured Magnetic Field. The distinct color scales are used to differentiate between the total anomaly values (nT) and the normalized data used for correlation analysis.

5.3 Multi-temporal Orthophoto comparison

Historical records indicate that the Salse di Nirano area has long been used for agriculture, livestock grazing, and other rural activities. Historical accounts, including Stoppani (1876), document the coexistence of these activities with the mud-volcano landscape, with cattle also reported in association with saline waters and active emission areas.

The area is currently designated as a protected natural reserve (established in the early 1980s). Orthorectified aerial imagery from 1976, available through regional geoportals, nevertheless provides clear evidence of a landscape strongly influenced by agricultural use, with extensive cultivated fields and reduced morphological expression of mud volcanic features.

Figure 11 compares the 1976 orthophoto with a recent (2024) orthophoto. The visual comparison highlights that zones corresponding to present-day active vents broadly coincide with areas characterized by tonal anomalies or heterogeneous surface textures in the historical agricultural landscape. This observation suggests a degree of spatial persistence in emission-prone zones, although it should be interpreted as a qualitative correspondence rather than a precise spatial match.

To enhance visual interpretation, contrast-enhanced representations were generated using color remapping tools (CorelDRAW). This processing was applied exclusively for visualization purposes in order to improve the distinction between land cover types (e.g., vegetation, bare soil, and cultivated areas) and does not affect the underlying spatial data.

Overall, the comparison between historical and modern imagery documents a marked transition from intensively cultivated land to a protected natural environment, while also suggesting a broad persistence of the main zones of surface emission activity.

Recent satellite imagery and publicly available remote sensing datasets do not show evidence of abrupt or anomalous activity within the Salse di Nirano system within the spatial and temporal resolution of the available datasets. The observed behavior is consistent with a system characterized by continuous and low-intensity degassing

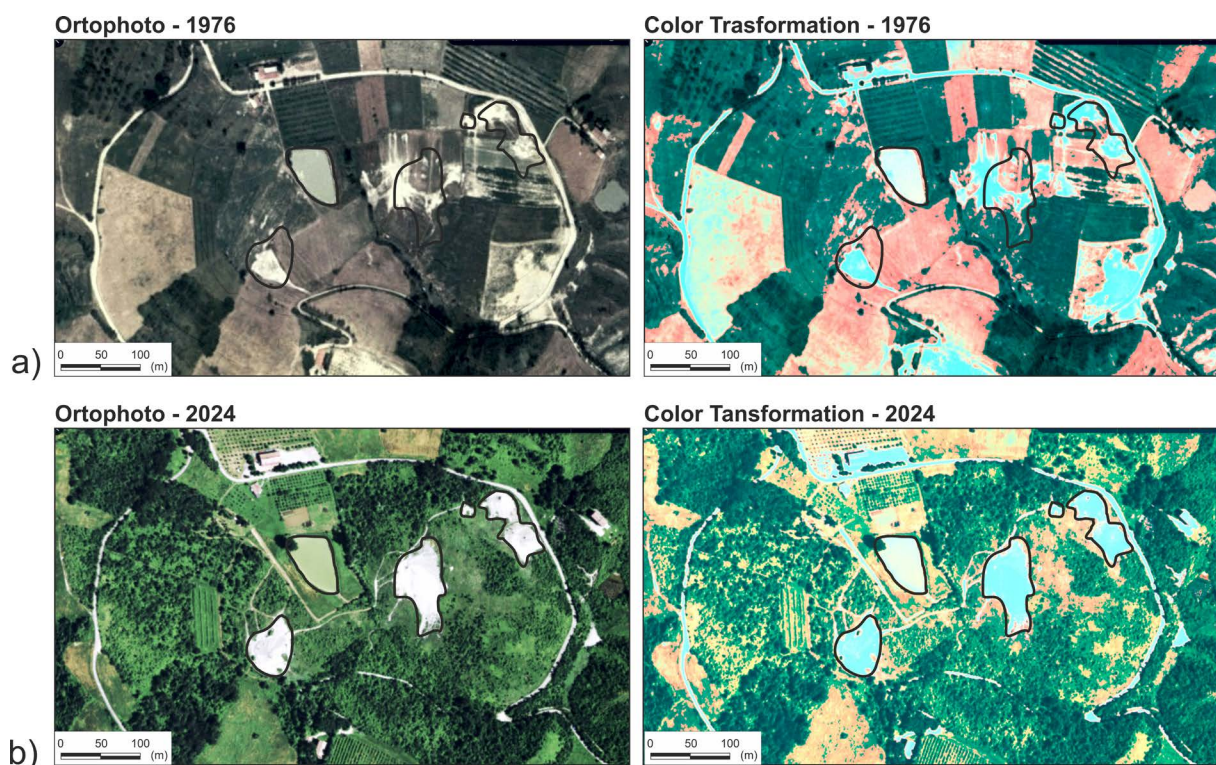


Figure 11. Land-cover evolution and emission vent stability (1976-2024). (a) 1976 orthophoto and corresponding false colour transformations. (b) 2024 Orthophoto and corresponding false colour transformations. Black outlines highlight the strong spatial correspondence between historical grayish patches and present-day active vents, indicating long-term stability of the main discharge areas despite the transition from intensive agriculture to current land cover.

processes, with variability likely controlled by environmental and seasonal factors. It is important to note that a detailed characterization of present-day emission dynamics lies outside the scope of this study, primarily focused on the reconstruction and interpretation of historical and cartographic data.

5.4 Complementary Geophysical Data

The Nirano mud volcano system has recently been extensively investigated through geoelectrical and structural studies, which have provided interesting constraints on subsurface fluid migration and the structural control of surface emissions (e.g., Romano et al., 2023; Nespoli et al., 2024; Giambastiani et al., 2024). Building on these previous works, the available electrical resistivity tomography (ERT) data were compared with the magnetic profiles acquired in this study in order to explore possible first-order spatial correlations between independent geophysical signals within a common geometrical framework (Fig. 12). This section aims to integrate the available geophysical observations into a coherent preliminary framework, exploring possible relationships among resistivity,

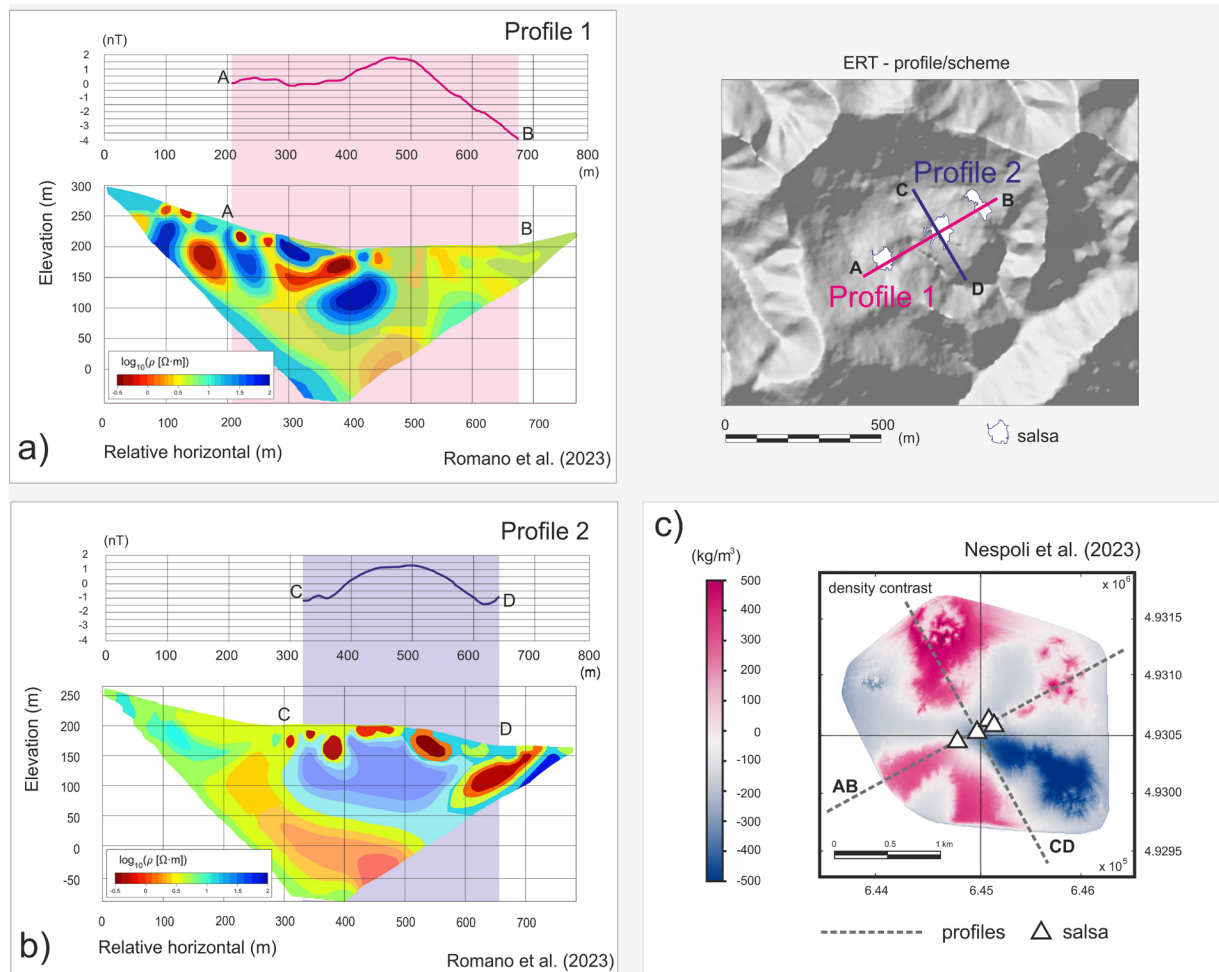


Figure 12. Integrated geophysical framework of the Nirano mud volcano system. (a,b) Electrical resistivity tomography (ERT) sections along the two investigated profiles, with corresponding geomagnetic data acquired along the same transects; A-B and C-D indicate the respective profile traces and allow direct spatial correspondence with their location on the map. (c) gravity-derived density contrast map of the study area, showing the location and orientation of the geophysical profiles. The ERT sections suggest a heterogeneous subsurface characterized by conductive clay-rich domains (warm colors) alternating with more resistive bodies (cold colors), possibly associated with gas-saturated zones and/or relatively competent lithological units. Figures modified after Romano et al. (2023) and Nespoli et al. (2024) for visualization and comparison purposes. The inset map (upper right) shows the study area and profile distribution.

magnetic, gravimetric, and structural features within the shallow plumbing system. The two orthogonal profiles cross the central sector of the mud volcano field, providing a first-order geometrical overview of the shallow subsurface. The ERT sections reveal a markedly heterogeneous resistivity distribution, characterized by alternating conductive and resistive domains with strong lateral variability. Conductive sectors are likely associated with water-saturated clay-rich sediments, whereas the more resistive anomalies may reflect localized gas accumulations and/or relatively competent lithological bodies. Notably, the resistive domains do not define a continuous vertical structure, but rather appear fragmented and laterally discontinuous along both profiles. This spatial arrangement suggests that fluid ascent is likely distributed through multiple preferential pathways within a structurally heterogeneous medium, rather than being confined to a single well-developed conduit.

The magnetic data display low-amplitude but coherent variations along both profiles, with local maxima spatially corresponding to sectors where the ERT sections image deeper or more structured anomalies. Although subtle, these magnetic variations may reflect localized mineralogical or physical changes possibly associated with fluid circulation along preferential ascent pathways, potentially involving processes occurring below the effective investigation depth of the resistivity data.

Overall, the observed geophysical patterns are consistent with a structurally controlled system in which fluid ascent is distributed through a heterogeneous and faulted subsurface, in agreement with the structural framework proposed in previous studies (e.g., Giambastiani et al., 2024). The combined comparison of ERT, magnetic, and gravimetric observations suggests that the shallow expression of the Salse results from the interaction between gas, saline fluids, and clay-rich sediments within a tectonically controlled environment characterized by strong lateral heterogeneity.

6. Discussion and Preliminary Conclusion

The Salse di Nirano represents one of the most relevant mud volcano systems at the boundary between the Po Plain and the Northern Apennines. Its origin is linked to the regional compressional tectonic regime, which has progressively deformed sedimentary successions and promoted fluid overpressure within deep horizons. Under these conditions, overpressured muds and fluids migrate upward through fractures and structural discontinuities, giving rise to mud volcanoes, gas emissions, and mud pools.

From a geomorphological standpoint, the area reflects the interaction between structural control and long-term surface processes. Unlike the surrounding dissected Apennine piedmont, the Nirano sector is characterized by a distinctive depressed basin surrounded by irregular ridges and badland-like slopes. Within this setting, the mud volcano field forms a clustered system of active and inactive vents distributed across a gently partitioned terrain, organized into two main morphological sectors separated by a central drainage axis.

Historical evidence indicates (Table 1; Fig. 6) long-standing scientific and local awareness of the phenomenon, while more recent records document significant anthropogenic modification prior to the establishment of the protected area in the 1980s. In particular, late twentieth-century aerial imagery shows an agricultural landscape in which muddy and clay-rich surfaces were still clearly visible and spatially consistent with present-day emission zones, indicating notable persistence of active centres through time.

The integration of historical cartography with UAV-based photogrammetric data enabled the reconstruction of a multi-temporal surface framework (Figs. 6-7). Despite the inherent uncertainties of historical sources, particularly those related to scale accuracy and interpretative bias, the comparison between the 1906 reconstruction and present-day morphology highlights both anthropogenic landscape transformation and stability of the main emission zones over historical timescales. The most pronounced morphological changes occur in the western sector, where a previously low-relief surface has evolved into a more elevated, cone-dominated morphology (Fig. 6).

Importantly, the persistence of the main emission zones does not imply morphological stability of individual mud-volcano structures. Rather, the historical and modern datasets suggest that local surface configurations may evolve substantially through erosion, sediment accumulation, vegetation growth, anthropogenic modification and changes in vent activity, while the broader spatial organization of emission-prone areas remains comparatively persistent. This distinction is relevant because it suggests that long-term structural controls may remain active even where their surface expression changes through time. The western sector provides a particularly clear example, showing marked morphological evolution within a spatial framework that remains compatible with the historical distribution of activity.

Geomagnetic data provide complementary constraints on subsurface structure (Fig. 8). The observed magnetic field exhibits a complex spatial pattern that only partially correlates with surface morphology. A main positive anomaly extends from the central emission area toward the southeast, while additional anomaly clusters occur in the northern and western sectors. Relative magnetic lows dominate the northeastern and southeastern portions of the study area (Fig. 8c).

Comparison with a simplified topography-induced magnetic model indicates that the observed anomalies cannot be explained by surface effects alone, suggesting a dominant contribution from subsurface sources. Moreover, the spatial organization of anomalies shows partial consistency with the regional structural framework, including a NW-SE-oriented anticline axis. However, the presence of distinct anomaly clusters, particularly in the western sector, suggests the possible existence of multiple subsurface pathways rather than a single feeding system. This interpretation is also consistent with the comparison with previously published geoelectrical and gravimetric observations, which indicate a laterally heterogeneous shallow subsurface rather than a simple vertically organized conduit system. The lack of a one-to-one correspondence between surface morphology, magnetic anomalies and resistivity structures should therefore not necessarily be interpreted as inconsistency among datasets. Instead, it may reflect the different physical properties and investigation depths sampled by each method within a complex system in which fluids migrate through multiple structurally controlled pathways.

Overall, the integration of historical data, UAV-derived models, and geomagnetic measurements provides a coherent multi-source perspective on the Salse di Nirano system (Figs. 6-8; Table 1). The results highlight the strong coupling between structural control and surface evolution, alongside the remarkable spatial persistence of emission zones over the past century despite significant anthropogenic modification.

A methodological implication of this study is that historical datasets, even when characterized by lower spatial resolution and unavoidable uncertainties, can provide useful quantitative or semi-quantitative constraints when their internal consistency is independently evaluated and when they are interpreted at an appropriate spatial scale. Their value therefore lies not in reproducing modern survey accuracy, but in extending the observational window beyond instrumental monitoring and providing a historical reference against which present-day high-resolution measurements can be evaluated. This aspect may be particularly relevant for slowly evolving geological systems for which modern monitoring covers only a small fraction of their activity history.

At the same time, the proposed approach has clear limitations. The historical DEM cannot support fine-scale metric interpretation comparable to modern UAV products, and the magnetic analysis presented here is intentionally exploratory rather than a full quantitative inversion. Consequently, the relationships proposed among surface evolution, magnetic anomalies and subsurface structures should be regarded as first-order constraints rather than unique solutions. Additional geophysical observations are required to test these interpretations and better characterize the geometry and continuity of the inferred fluid pathways.

Within these limitations, the integrated use of heterogeneous datasets represents a step toward a transferable multi-source framework for investigating mud volcano dynamics over historical timescales. The approach can potentially be applied to other sites where archival cartography, historical imagery or descriptive records are available together with modern remote-sensing and geophysical observations. In this perspective, the workflow contributes to the objectives of the ProMud project by providing a strategy for combining datasets that differ substantially in origin, resolution and scientific meaning.

Future investigations will expand this approach through dedicated geophysical campaigns, including active and passive seismic surveys, electrical resistivity tomography and extended UAV-based magnetometric coverage, with the aim of improving the characterization of the shallow subsurface system controlling mud volcano activity.

Data availability statement. Data are available from the authors upon request.

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