

Engineering geological model of the Cixerri Plain (Sardinia, Italy) based on integrated geophysical investigations for sinkhole hazard assessment

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ABSTRACT

The Cixerri Plain (SW Sardinia, Italy) is characterised by numerous sinkholes that pose a major hazard to farmland and strategic infrastructures. An engineering geological model was developed to detect subsiding areas and the possible presence of subsurface cavities that may evolve into sinkholes, by constraining predisposing factors and attempting to assign the well-known mechanisms controlling their evolution. The approach integrates single-station ambient noise measurements, nanoseismic monitoring, and multitemporal topographic surveys, including LiDAR and GNSS/UAV-derived digital elevation models (DEM). Resonance frequencies and directional effects reveal a fault-controlled "horst and graben" architecture, enabling the estimation of the depth to the buried limestone bedrock beneath the continental deposits, which ranges from approximately 80 to 120 m in the deepest sectors. The HVNSR function drops below unity (deamplification) at resonance frequencies higher than 5 Hz, clustering near already existing sinkholes, suggesting partially emptied, low-cohesion horizons at depth. Furthermore, nanoseismic measurements allow to cluster microevents consistent with bedrock microcracking and cavity growth, supporting an active subsurface evolution. DEM differencing highlights both widespread subsidence and specific lowered zones (≈ 50 – 100 m) hosting sinkholes up to 6–8 m in diameter. These observations support a depth-dependent framework in which cover-collapse processes prevail where the bedrock is shallow, collapse-piping becomes dominant where the cover thickens, and hybrid behaviours occur in transitional sectors. These outcomes provide a basis for sinkhole hazard zoning and to attribute rating to monitoring and mitigation actions.

1. Introduction

Sinkholes are ground instabilities characterised by the collapse of shallow underground cavities that can pose significant threats to urban areas, especially when indicators of incipient deformation are absent. These phenomena have long been a major research topic for engineering geologists and environmentalists due to the complexities of their formation, evolution, and impacts on anthropogenic settlements and major infrastructures (Delle Rose et al., 2004; Gutiérrez et al., 2007, 2014). These ground instabilities exhibit a wide range of shapes and sizes, with occurrences varying from subtle ground subsidence to sudden, large-scale collapses that can reshape the landscape. The formation of sinkholes is often linked to the dissolution of soluble rocks, such as limestone, gypsum, or salt, resulting in the creation of underground cavities

(White, 1988; Waltham et al., 2005). The main triggering factors responsible for the collapse of near-surface cavities are highly diversified and strictly related to geological, hydrological, and anthropogenic processes (Gutiérrez, 2016).

The scientific study of sinkholes began in the late 19th century in the Trieste Karst, initially focusing on geomorphological aspects (Cvijic, 1893). Over time, their definition was refined by incorporating distinctions based on genetic and evolutionary mechanisms (Cramer, 1941). The term "sinkhole" was later introduced by the American scientific community to describe sudden, subcircular ground subsidence (Fairbridge, 1968). These features typically develop in areas where alluvial or volcanic sediments overlie a soluble and cohesive bedrock. The susceptibility of an area to sinkhole formation is primarily constrained by the geological setting, hydrological conditions, and the

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characteristics of sedimentary covers (Faccenna et al., 1993; Salvati and Sasowsky, 2002; Nisio, 2003). Several factors that can be regarded as critical for assessing potential susceptibility to sinkhole formation are related to the geo-structural setting, geometries and thickness of soil/rock covers, hydrogeological features regarding karst systems of infiltration waters, particularly with respect to pressure/water level oscillation, and chemical properties of groundwater.

Further investigations highlighted the need to distinguish subsidence phenomena in dolines and sinkholes, leading to a classification based on local geological settings, morphological features, and formation and evolution mechanisms (Nisio and Salvati, 2004). In fact, while dolines form in areas where karstified bedrock is either exposed or covered by a thin sediment layer, sinkholes can form beneath sediment covers exceeding 100 m (Nisio and Salvati, 2004). Furthermore, dolines develop through downward processes and result from dissolution processes concentrated in the epikarst (i.e., the surficial, fractured zone of karst; Stefanovski et al., 2024), whereas sinkhole formation typically starts at the bedrock-soil cover interface. At this boundary, proto-cavities form and propagate upward through progressive collapses driven by the dominant transport mechanism (i.e., raveling or piping) and the mechanical properties of the overlying sediments. The final collapse occurs when the bearing capacity of the soil layer between the underground cavity and the ground surface is exceeded, ultimately leading to the formation of funnel-shaped or subcylindrical sinkholes (Nisio, 2003). Despite these distinctions, the term *sinkhole* is frequently used as an overarching label for a broad range of subsidence phenomena. This improper usage often obscures significant genetic differences, since sinkholes may form rapidly or progressively due to processes such as solution, collapse, deep piping or even anthropogenic activities (Nisio, 2003; Waltham and Fookes, 2003; Waltham et al., 2005; Ford and Williams, 2007). To avoid ambiguity, the addition of qualifiers (e.g., “solution sinkhole”, “collapse sinkhole”, “cover-subsidence sinkhole”) highlights the dominant formation mechanism, which is crucial for accurate hazard assessment and the development of appropriate mitigation strategies (Gutiérrez et al., 2014). The use of precise terminology is especially important when differentiating among sinkhole types to determine subsurface conditions, potential failure modes, and the design of remedial strategies.

Detection, monitoring, and forecasting are crucial steps for zonation, susceptibility assessment, and risk mitigation in sinkhole-prone areas (Gutiérrez et al., 2007). In particular, geophysical surveying techniques such as passive seismic methods (Liang et al., 2018; Rao et al., 2021), ground penetrating radar (GRP) (Ebraheem and Ibrahim, 2019; Pilecki et al., 2021), microgravimetry (Arisona et al., 2023) and electrical resistivity tomography (ERT) (Cardarelli et al., 2006; Park et al., 2014) represent reliable and non-invasive tool for detecting and reconstructing the geometry of buried structures, and can provide useful insights into the presence and mechanical behaviour of potentially unstable underground cavities (Pazzi et al., 2018; Bonetto et al., 2023; Galone et al., 2024; Grechi et al., 2024). Non-invasive approaches are crucial in heavily urbanised areas, especially in historic cities where they often represent the only feasible subsurface exploration tool for identifying sinkhole-prone areas (Bianchi Fasani et al., 2011; Sevil et al., 2020). Geophysical investigations aimed at detecting subsurface cavities also benefit from integration with complementary field surveys, thereby enhancing the robustness and resolution of engineering geologic models. In fact, the use of a multidisciplinary approach allows for leveraging data redundancy and reducing interpretative uncertainty by combining borehole records and geotechnical data, remote sensing (e.g., SAR interferometry and photogrammetry), and hydrogeological or hydrogeochemical analyses. The combination of multiple techniques can improve the characterisation of the subsoil and inform more reliable risk assessments and targeted mitigation strategies. In this framework, this study adopted a multidisciplinary approach to evaluate the subsurface conditions of the Cixerri plane for enhanced sinkhole hazard assessment.

However, translating detailed site-specific analyses into a larger-scale hazard assessment necessitates identifying and quantifying the full spectrum of potential predisposing and triggering factors of ground instability. These factors are crucial for developing susceptibility maps, which serve as tools for land-use planning and management, particularly in densely populated areas. Accordingly, attention is often directed toward subsurface lithologies, hydrogeological conditions (Intrieri et al., 2018), and geomorphological and geotechnical parameters such as soil erosion and permeability (Nam et al., 2020). Moreover, the presence and evolution of anthropogenic cavities require careful examination (Guarino et al., 2018; Scotto di Santolo et al., 2018; Tufano et al., 2022), as well as the non-negligible influence of seismic activity (Tomac et al., 2023). Once these factors are identified, their impact and triggering potential quantified, reliable susceptibility maps can be produced and validated.

This paper contributes a process-based engineering geological interpretation of sinkhole development in a buried-karst plain, the sinkhole-prone Cixerri Plain (SW Sardinia, Italy), by adopting an integrated approach that links: (i) the fault-segmented geometry of the carbonate bedrock, (ii) the thickness and mechanical behaviour of the continental soft cover, and (iii) independent proxies of active subsurface evolution (HVNSR anomalies, nanoseismic microevents, and multi-temporal DEM differencing). Beyond a site-specific case study, the paper provides a transferable framework in which sinkhole-genesis mechanisms evolve with increasing bedrock depth, from cover-collapse (Waltham et al., 2005; Gutiérrez et al., 2007) to collapse-piping processes (Nisio, 2003; Caramanna et al., 2008), with hybrid behaviours in fault-bounded transitional sectors. The resulting engineering geological model supports process-based zoning criteria for prioritising monitoring and mitigation in similar karst settings. The goal is to enhance predictive capabilities and mitigate hazards associated with sinkhole formation by scrutinising the interplay among natural factors that drive sinkhole initiation and growth.

The originality of the study relies on the integration of rapid and non-invasive geophysical and morphological methods, able to define proxies of underground cavities, within a process-based engineering geological framework. Although the Cixerri Plain is included in the ISPRa National Sinkhole Database, recently updated (Nisio et al., 2026), and has long been recognised as a sinkhole-prone area, it has not previously been investigated in depth. Compared with other Italian sinkhole-prone areas the Cixerri Plain has received less specific attention from the perspective of process-based sinkhole hazard assessment. This study, therefore, contributes both a new site-specific model and a transferable methodological framework for covered karst plains where direct subsurface information is limited.

2. Geological framework of the study area

The Cixerri Plain is situated in southwestern Sardinia and represents a low-lying tectonic depression filled with alluvial sediments, bordered by low Palaeozoic metamorphic limestone reliefs and minor Oligo-Miocene volcanic deposits. The tectonic evolution of the Cixerri plain spans the Palaeozoic and Cenozoic, with the “Sardinian Discordance” (Teichmüller, 1931; Stille, 1939) marking a regional nonconformity that separates Cambrian-Lower Ordovician formations (Nebida, Gonnese, Campo Pisano, and Cabitza Formations) from Upper Ordovician-Carboniferous sequences. Cenozoic tectonics significantly shaped the Sulcis-Iglesiente area, forming the Campidano Graben (Carmignani et al., 1994) and the EW-oriented Cixerri and Narcao Basins, where the Sulcis-Iglesiente region became a horst bordered by the Campidano Fault to the east and the Sardinian platform faults to the west (Lecca et al., 1986). The Cixerri and Narcao Basins, interpreted as mild synclines from the Oligocene, exhibit sub-vertical axial planes (Carmignani et al., 2004). Two Pliocene tectonic systems have influenced the structural setting of the hills bordering the Cixerri Plain: an older east-west and a more recent north-south (N-S) fault system (Funedda et al.,

2009). The E-W trending faults display a weak right-lateral strike-slip component, placing the Cixerri Formation in contact with Palaeozoic basement. In contrast, the north-south faults, such as the Zinnigas Fault, truncate the basement and the Cixerri Formation, reaching offsets up to

100 m, and are sealed by Pleistocene alluvial deposits (Funedda et al., 2009).

The stratigraphy of the Cixerri plain includes (Carmignani et al., 1982; Funedda et al., 2009): i) Palaeozoic metamorphic basement; ii)

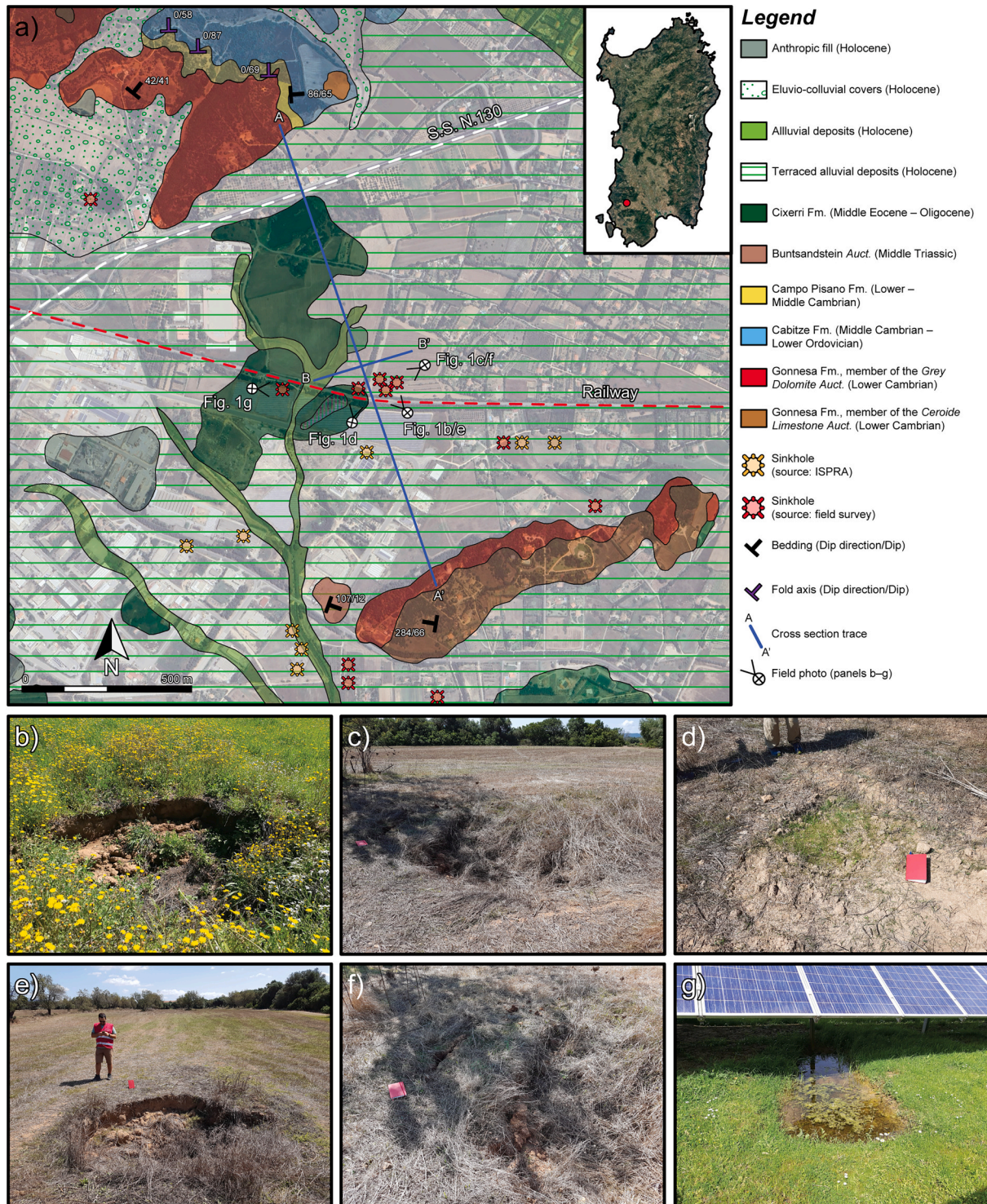


Fig. 1. Geological map of the Cixerri Plain showing the sinkholes by field surveys, technical reports and catalogued by ISPRA over the recent years (see the National Sinkhole Database of Italy - <https://sgi.isprambiente.it/sinkholeweb/>) (a). Photographs of sinkholes detected in the study area during the field surveys conducted in 2018 are reported in the bottom part of the panel. Photographs 1b and 1e show the same sinkhole five months apart: an enlargement of the shape can be observed. Photograph 1c shows the largest sinkhole detected in the study area, with a detailed view of the tension cracks forming a halo around the main circumference (f). Photograph 1d shows an incipient sinkhole where subsidence and halo tension fractures can begin to be seen in the immediate vicinity. Finally, photograph 2 g shows a subsiding area, not yet evolved into a sinkhole, with the piezometric surface emerging. The photographs are original field photographs taken by the authors and show representative sinkholes, tension cracks and subsiding areas observed at the time of field investigation.

Late Palaeozoic intrusive and veining complex; iii) Tertiary volcano-sedimentary succession; iv) Quaternary deposits (Fig. 1a). The following lithostratigraphic units are located near the study area (Funedda et al., 2009):

- Nebida Formation ("Sandstones" *Auct.*) (Lower Cambrian): Metasiltstones and quartz metasandstones (~220 m thick), deposited in shallow marine to sabkha environments;
- Gonnese Formation ("Metalliferous" *Auct. p.p.*) (Lower Cambrian): Carbonate-dominated deposits formed in supra- to sub-tidal settings with significant mineralisation (~200–500 m thick);
- Campo Pisano Formation ("Calceschisti" *Auct.*; "Metalliferous" *Auct. p.p.*; "Nodular Limestone" *Auct.*) (Lower - Middle Cambrian): Nodular limestones with silty shale interlayers, formed in a shallow hypoxic sea (~21 m thick);
- Cabitza Formation ("Cabitza Shale" *Auct.*, "Laminated Shale" *Auct.*) (Middle Cambrian – Early Ordovician): Rhythmic alternation of metargillites and metasiltstones with tidal influence (~150 m thick).

The post-"Sardinian Unconformity" succession (Middle Ordovician–Lower Carboniferous) rests in angular unconformity on the Cabitza Formation, beginning with coarse deposits rich in olistoliths, transitioning to finer clastics, and culminating in syntectonic sediments with volcanic input (Loi and Dabard, 1997).

Middle Eocene–Oligocene sediments dominate the Cixerri Valley (Funedda et al., 2009). The Cixerri Formation forms the Cixerri valley's alluvial bedrock (Balía et al., 2001; Funedda et al., 2009) and consists of: i) breccias and conglomerates (poorly sorted, polygenic); ii) grey/yellowish clays with hematite nodules (paleosol indicating humid climate); iii) quartz-feldspathic sandstones with conglomerate lenses (interpreted as paleo-riverbeds); iv) red clays and purplish-red siltstones (fluvial-lacustrine environment). Outcrop thickness reaches 40 m, but boreholes in the Sulcis basin record up to 300 m.

Quaternary deposits unconformably overlie the Cixerri Formation (Funedda et al., 2009) and are listed in the following:

- Porto Vesme Synthem (Pleistocene): Terraced alluvial fans (~5 m thick);
- Terraced alluvial deposits (Holocene): Gravel deposits in inactive terraces, locally exceeding 10 m thickness (Funedda et al., 2009);
- Alluvial deposits (Holocene): Fluvial deposits from local water-courses (Flumini Mannu, Riu Cixerri), up to 5 m thick (Bondesan et al., 1999; Funedda et al., 2009).

Structural and lithological controls define the Cixerri Plain's geomorphology, with selective erosion shaping areas with silty-sandy lenses of the Cixerri Formation and tertiary volcanic necks (Funedda et al., 2009). Pleistocene and Holocene river dynamics dominate the region, in which alluvial fans have evolved into terraces.

The local hydrogeological units (Nisio, 2008) include:

- Lower terrigenous complex: regional aquiclude (~800 m thick), composed of rocks belonging to Nebida Formation;
- Ancient carbonate complex: includes Gonnese and Campo Pisano Formations, with significant karstification in limestone portions (~500–1000 m thick);
- Intermediate schist complex: low permeability (~300–400 m thick), comprising the upper Campo Pisano and Cabitza Formations;
- Upper terrigenous complex: Post-"Sardinian Discordance" succession (~200–500 m thick), forming a lateral permeability barrier for the Cixerri Plain's aquifers.

The Cixerri Basin acts as a recharge zone for the regional carbonate aquifer (Ardau et al., 2007). Karst networks (~4000 m known extent) facilitate rainwater infiltration, supporting hydraulic continuity between upstream and downstream carbonate systems beneath the alluvial

cover (Atzeni et al., 1994).

2.1. Geohazards in the Cixerri Plain

Sinkholes have always represented the primary geological hazard in the Cixerri Plain (Balía et al., 2001; De Waele and Muntoni, 2001; Ardau et al., 2007; Bianco, 2007; Nisio, 2008; Caredda et al., 2010; Mureddu, 2015), with the earliest documented collapse dated back to the 1st century BCE (Plinio Il Vecchio).

The Cixerri Plain shares several characteristics with other sinkhole-prone areas in Italy (Nisio and Salvati, 2004), including: i) a deeply buried karstified bedrock overlaid by a sediment cover of more than 100 m; ii) a continental cover with variable granulometry and poor geomechanical properties; iii) a karst hydrogeological system within the bedrock; iv) the presence of tectonic structures fostering fluid migration and acting as preferential pathways for subsurface deformation (Faccenna et al., 1993).

In the Su Merti area, sinkholes typically feature sub-circular shapes, with diameters ranging from a few meters to approximately 20 m and depths not exceeding 10 m (Balía et al., 2001; De Waele and Muntoni, 2001; Nisio, 2008) (Fig. 1b–g). One notable event occurred in October 1998, when an 18-m-wide, 15-m-deep sinkhole formed without precursory signals near the railway track (Balía et al., 2001). Seasonal water accumulation has been observed at the bottom of the sinkhole (Bianco, 2007). Interestingly, this event took place overnight in a recently ploughed field, highlighting the potential role of anthropogenic activity in sinkhole formation. Due to such occurrences, the area was included in the Sinkhole Project led by the Italian Institute for Environmental Protection and Research (ISPRA, 2002).

In this framework, two well-known genetic models explain sinkhole formation in the Cixerri Plain. The first model interprets them as cover-collapse sinkholes (De Waele and Frau, 2001; De Waele and Muntoni, 2001; Ardau et al., 2007). In this case, cohesive sediments overlying the bedrock inhibit piping and allow a void to gradually develop. Once the thickness of the overlying material decreases to a critical threshold, thereby causing a loss of bearing capacity, the roof collapses abruptly. These sinkholes often host groundwater circulation due to the presence of alluvial aquifers.

The second model attributes sinkhole development to shallow piping processes (Balía et al., 2001). This mechanism becomes relevant when the carbonate bedrock lies at depths less than 20 m, and the cover does not exceed 30 m. Under these conditions, cover-subsidence sinkholes can form in flat or gently depressed areas that promote high infiltration rates through fracture networks and karst conduits (Ardau et al., 2005). Groundwater table fluctuations driven by heavy rainfall or prolonged droughts can generate turbulent flow, therefore accelerating sediment removal by ravelling and initiating subsidence (Ardau et al., 2005).

3. Materials and methods

Geophysical investigations and remote surveys were carried out to reconstruct the engineering geological model of the Cixerri Plain for sinkhole mapping and zonation purposes. The datasets were integrated following a cross-consistency and cross-validation criterion, in which each method was used to constrain a different component of the sinkhole system pointed out by the others.

3.1. Ambient seismic noise measurements

Due to limited information on the local geological context, we performed ambient seismic noise measurements to identify shallow geological structures and locate underground cavities (Fig. 2). To this aim, we recorded ambient vibrations using three-component velocimeters (SARA SL06, nominal frequency 2 Hz) set at a sampling frequency of 200 Hz. We performed 99 measurements over two field campaigns in April and September 2018, recording ambient vibrations for at least 1 h

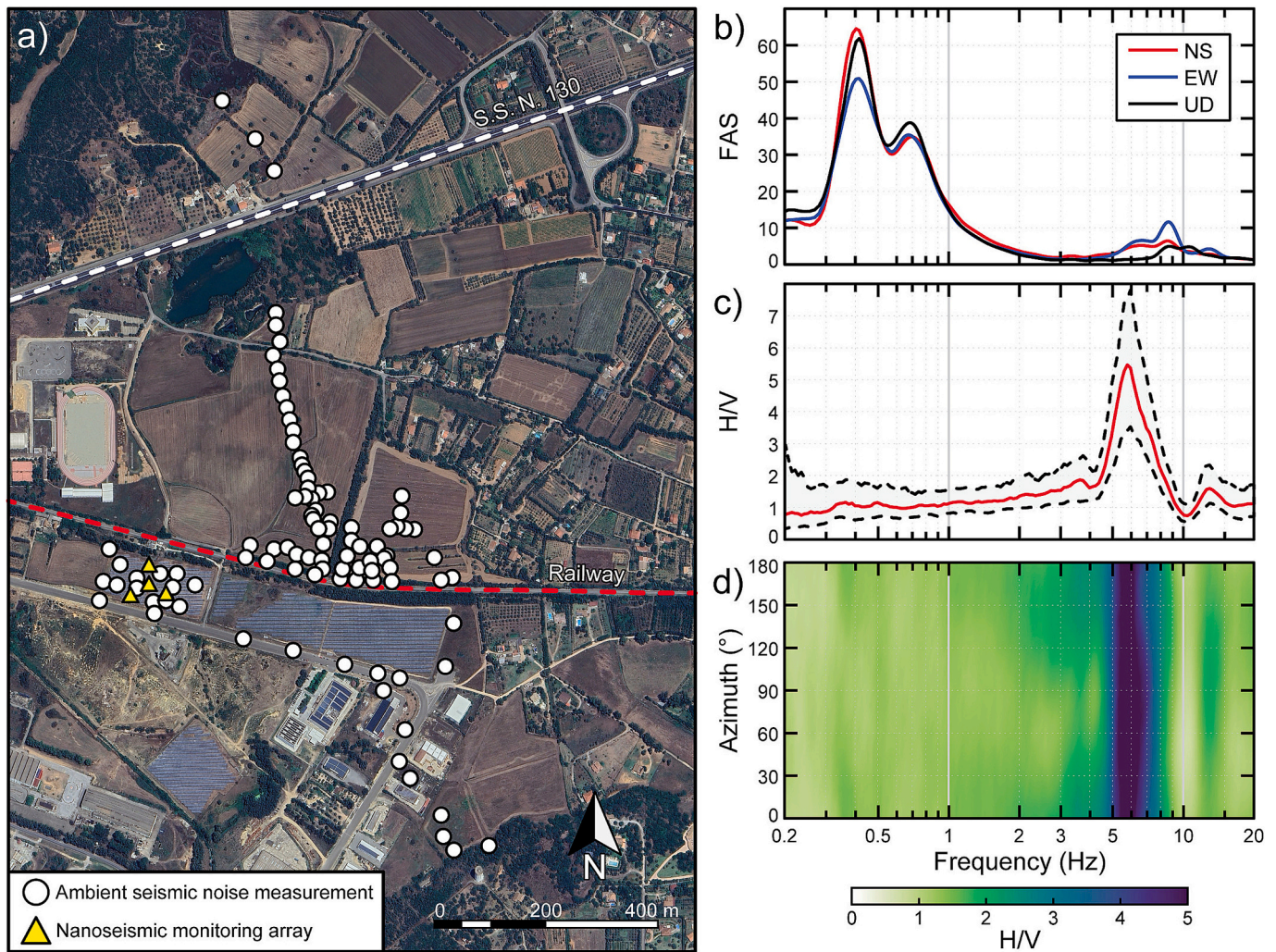


Fig. 2. Satellite view of the study area showing the location of the nanoseismic monitoring array and ambient seismic noise measurements (a). Example of results from ambient seismic noise processing showing a marked drop in the HVNSR function at 10 Hz (c) and no polarisation effects (d), which suggests the possible presence of a near-surface cavity.

under stable weather conditions to avoid meteorological disturbances. We used the Horizontal-to-Vertical Noise Spectral Ratio (HVNSR) technique (Nogoshi and Igarashi, 1970; Nakamura, 1989) to identify and map the distribution of local fundamental frequencies (f_0) likely related to marked impedance contrasts between the shallow soft soil layer and the buried bedrock (Bour et al., 1998; Haghshenas et al., 2008).

We utilised the open-source software Geopsy (Wathelet et al., 2020) to process the ambient seismic noise dataset, following the recommendations provided by the SESAME Project (https://sesame.geopsy.org/Delivrables/Del-D23-HV_User_Guidelines.pdf). Initially, each 1-h recording was bandpass-filtered between 0.25 and 20 Hz, detrended, and segmented into non-overlapping 40-s windows with a 5% cosine taper. We then computed the fast Fourier transform (FFT) for each segment, and the resulting spectra were smoothed using a Konno-Ohmachi filter with bandwidth coefficient $b = 40$ (Konno and Ohmachi, 1998) prior to computing spectral ratios. Results were averaged over all windows to reduce variance and obtain mean HVNSR values.

Most measurements were performed within the Cixerri Plain following an NNE-SSW cross-section between two outcropping bedrock sites (section AA', Fig. 1a). Some measurements were performed immediately north and south of the railway, where the sinkholes previously investigated by Balia et al. (2001) were detected. In addition to

identifying peaks in HVNSR functions associated with stratigraphic resonances, we analysed the directivity of spectral ratios to investigate the presence of buried tectonic elements in the study area, as suggested by Balia et al. (2001). The shape of the HVNSR(f) function was also accounted for in case of sudden amplitude drops after well-pronounced peaks at frequencies higher than 5 Hz, resulting in a deamplification, that may indicate an inversion in the S-wave velocity profile, potentially related to the presence of underground cavities (Castellaro and Mulargia, 2009; Panzera et al., 2013; Di Giulio et al., 2014; Panzera et al., 2015).

3.2. Nanoseismic SNS array

To detect microseismic events associated with hypogeous instabilities, which could indicate the development of underground caves, we performed a nanoseismic monitoring survey using a Seismic Navigating System (SNS) array configuration (Joswig, 2008). The SNS array consisted of four short-period velocimeters: one three-component sensor at the centre and three vertical-component sensors deployed at 120° intervals and distances ranging from 25 to 100 m. The array aperture depends on the expected hypocentral distance of the events from the central station. This SNS array technique guarantees a hypocentral location uncertainty of approximately 10% of the epicentral distance from the central station (Walter et al., 2012a, 2012b). Each SNS array

operated for approximately four days during the April 2018 field campaign. The station was equipped with a LE-3Dlite MkII seismometer, a REFTEK 130–01 datalogger set to a sampling frequency of 500 Hz, and a GPS antenna for accurate synchronisation.

Nanoseismic monitoring is an advanced passive seismic technique initially developed to detect local earthquakes induced by mining activities in the Ruhr basin (Germany) through pattern recognition analyses (Joswig, 1995). After successful applications in forensic seismology (Douglas, 2007), the method now complements passive seismic and microseismic monitoring (Joswig, 2008; Sick et al., 2014), exploiting their main features, such as resolving events with low signal-to-noise ratio (SNR) and localising the hypocentre, onset time, and local magnitude (ML) even for events with magnitudes below 0. Examples of applications of the method are related to sinkhole monitoring (Wust-Bloch and Joswig, 2006), active faults mapping (Häge and Joswig, 2009a, 2009b), as well as monitoring of unstable slope dynamics (Walter and Joswig, 2009; Fiorucci et al., 2017; Iannucci et al., 2020a, 2020b).

The dataset acquired by the SNS array was processed and analysed using the NanoseismicSuite software (www.sonicon.com), which includes two main tools: SonoView for event detection and HypoLine for event location. SonoView enables the manual detection of events on the computed supersonogram, which results from the sonograms calculated at each array station (Sick et al., 2014). A sonogram is a spectrogram in which the stationary background noise has been removed (Joswig, 1995), and it utilises a colour palette where increased saturation indicates higher amplitude signals, thereby aiding the identification of microseismic events. The event magnitude (ML) is computed at the central station of the array by using the maximum signal amplitude recorded across all three components. The subsurface model used in this study assumes an infinite and homogeneous lower half-space, incorporating data on seismic wave propagation velocity and Poisson's ratio for the carbonate bedrock derived from Balia et al. (2001): to constrain the seismic shear-wave velocity (V_s) model, we adopted $V_s = 1680$ m/s, derived from V_p , and a weighted-mean $V_s = 1280$ m/s computed by averaging 1680 m/s with $V_s = 360$ m/s for the shallow surficial deposits. Characteristics of the carbonate bedrock were derived from Balia et al. (2001).

In this study, we used the SNS array to locate low-magnitude events and to gain insights into the evolution of sinkholes in the area of investigation. The primary goal of this analysis was to identify clusters of events and analyse their features in terms of duration, temporal distribution, and frequency content. The results were then compared with the geological model of the plain and integrated into the proposed genetic and evolutionary model of the sinkholes for the area.

3.3. Geomorphological surveying

We carried out topographic surveys to identify potential subsidence phenomena associated with the formation of underground cavities, utilising GPS-GNSS (Global Navigation Satellite System) measurements, 3D Total Stations, and UAS (Unmanned Aerial System) to obtain high-resolution digital terrain elevation models (DEMs). Three surveys were performed in July 2017, April 2018, and September 2018. The instrumentation used for these surveys included a Leica Viva GS14/CS15 GPS/GNSS equipped with a Galileo antenna, a 3D Leica MS60 Total Station, and a DJI Spark drone.

The GPS dataset was collected in RTK differential mode with a single baseline (Baratin and Grassi, 2010), utilising the ITALPOS GNSS permanent antennas located in the Sardinia Region. The Leica Geo Office software (www.leica-geosystems.com) was used to manage field data and for preliminary data analysis, including the study of GPS, GNSS, and Galileo almanacs. We used the Verto2k software (www.igmi.org) from the Military Geographical Institute of Italy (IGM) to compute orthometric heights using the undulation model of the gravimetric geoid (ITALGEO2005) and to correctly convert geographical coordinates

according to IGM standards (Barzaghi et al., 2007). Data processing was performed in a GIS environment to generate DEMs using the Inverse Distance Weighting (IDW) interpolation algorithm. Finally, we reconstructed a 1×1 m DEM from a 2008 LiDAR survey (provided by the Ministry of the Environment - <http://www.pcn.minambiente.it/viewer/>) to extend the time interval for the morphological evolution analysis of the site. This step enabled us to compare the three DEMs at the same spatial resolution.

4. Results

We used the HVSNR from all seismic noise measurements to reconstruct the near-surface engineering geological model of the valley by inverting the fundamental resonance frequencies of the site and estimating the depth of the bedrock-soft soil contact. Furthermore, we tried to locate shallow underground cavities in the soft soil by identifying sharp drops in the HVNSR function, resulting in a deamplification and associated with local resonances of complex roofs, as they can be interpreted as linked to relevant seismic wave velocity inversion along the seismo-stratigraphic log (Vella et al., 2013).

The local fundamental resonance frequencies in the Cixerri Plain range from 2 Hz to 15 Hz, and secondary resonance peaks were observed in only some of the measurements. Analysing the distribution of resonance frequencies and their polarisation (Fig. 3), a particular arrangement is observed in the vicinity of a sinkhole that formed in 1998.

Based on the HVNSR results, we identified distinct resonance frequencies and polarisation clusters and divided the study area into three sectors associated with different response models:

- Northern sector (sector N; red dashed box in Fig. 3), where the fundamental frequency is lower than 4 Hz with a marked EW direction of polarisation.
- South-eastern sector (sector SE; orange dashed box in Fig. 3), with fundamental frequencies ranging 4–7.5 Hz, and direction of polarisation from NW-SE to W-E.
- South-western sector (sector SW; blue dashed box in Fig. 3), where resonance frequencies range from 10 Hz up to 13 Hz, with predominant NE-SW polarisation.

A further cluster emerges in the southwestern area of the Plain, near the bedrock outcrop. Here, moving southward, resonance frequencies gradually shift from average values of 6–7 Hz to isolated values of 4 Hz and then rise abruptly up to 14 Hz. At the same time, the polarisation of the HVNSR peaks exhibits marked variations between the central measurements and those collected at the margins (Fig. 3).

Measurements showing a sudden drop in the HVNSR curve are predominantly concentrated in the southeastern sector (SE) of the study area. This sector also coincides with the zone where most sinkholes have been mapped (Fig. 4).

Concerning the data collected from the SNS array, we manually screened the recordings using the supersonograms to exclude false or noisy events from further analysis. Hence, we reconstructed a preliminary dataset of 170 microseismic events, among which 20 events were classified as microcracking of the buried bedrock. The epicentres of these events cluster into three sectors (Fig. 4), one of which coincides with the area where most sinkholes have been inventoried. The local magnitude (ML) of these events ranges from -2.6 to -0.9 , with an average value of -1.7 . These values are consistent with those associated with microseismic events that have likewise been interpreted as microcracking phenomena within the rock mass in similar carbonate and karst settings (Wust-Bloch and Joswig, 2006; Fiorucci et al., 2017; Iannucci et al., 2020a).

We performed multi-temporal morphological surveys to integrate geophysical investigations in the Cixerri Plain, where sinkholes have historically posed significant hazards. A Triangulated Irregular Network (TIN) algorithm was applied to GPS data in the photogrammetric aerial

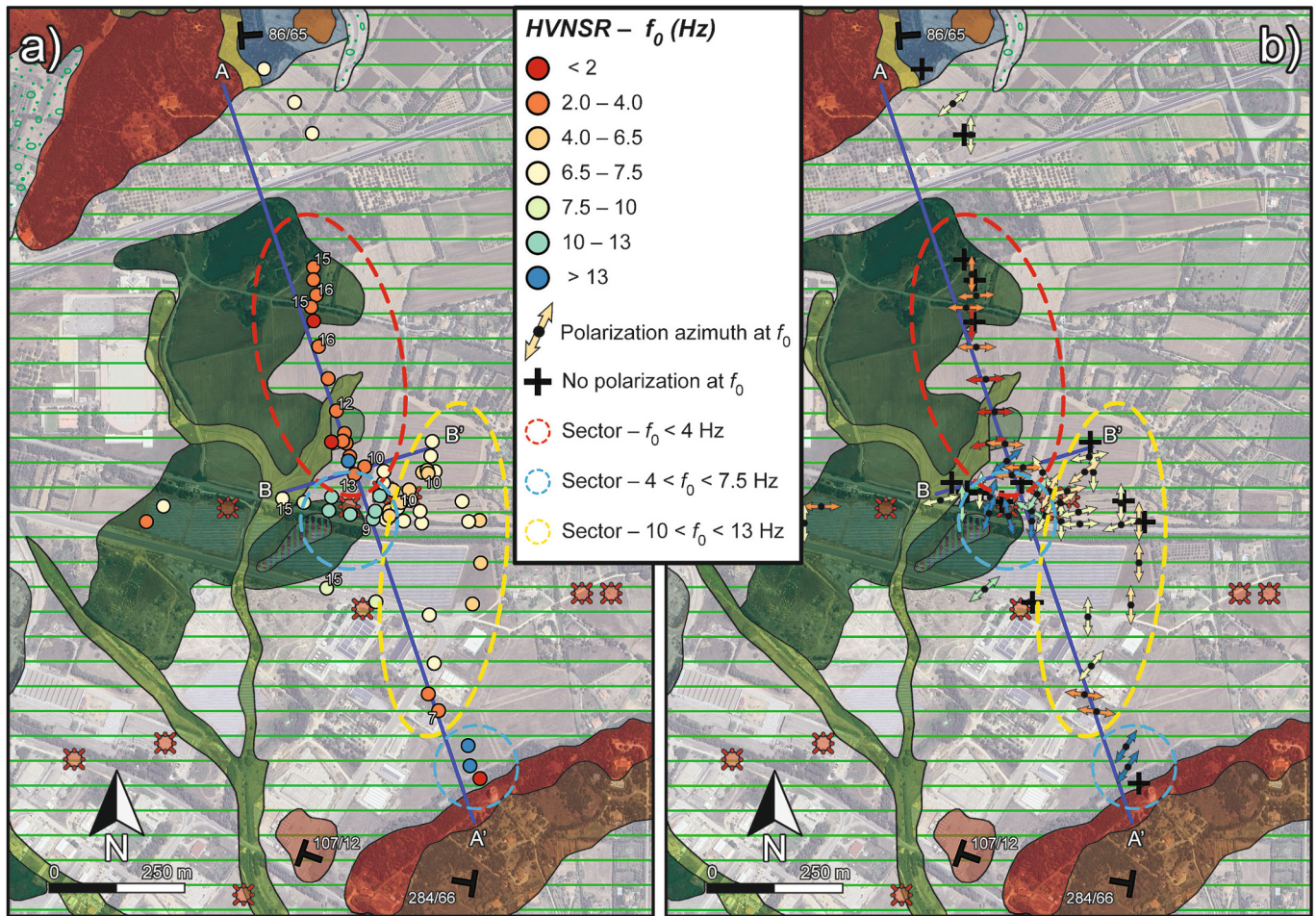


Fig. 3. (a) Frequency distribution map of the first resonance peak derived from Horizontal to Vertical Noise Spectral Ratio (HVNSR) analysis and projected onto a geological base (see Fig. 1 for its legend). Labels above some symbols indicate the frequency of the second resonance peak. Only class A and B measurements (SESAME) are shown. (b) Map of directivity (azimuth) for the first resonance peak derived from HVNSR analysis, projected onto a geological base (see Fig. 1 for its legend). The directivity (azimuth) is visually represented by the rotation of the rod-shaped symbol, while the colour scale provides information about the frequency.

analysis, which revealed that the examined area includes evidence of both buried sinkhole relicts (e.g., the one formed in 1999) and active landforms.

Using GPS data collected during the 2017 and 2018 GPS campaigns, we generated digital elevation models (DEMs) using an Inverse Distance Weighting (IDW) interpolator, which is particularly suitable for modelling landforms. We then compared these DEMs with the 2008 DEM retrieved from the national database (<http://www.pcn.minambiente.it/mattm/en/>). Fig. 5 (c–e) shows this comparison by juxtaposing the terrain models from all surveys against the orthophoto generated from the 2018 drone flight. In 2008, the only visible feature was the unfilled 1999 sinkhole, which resulted in a maximum elevation difference of approximately 7 m between the 2008 and 2018 DEMs. On the other hand, the central north–south-oriented depression, absent in 2008, developed in subsequent years and became clearly visible in later surveys.

The 2017 and 2018 DEMs show consistent results: the central lowered area persists, while a new lowered zone extends westward from the filled sinkhole. Two small sinkholes are identifiable in both datasets. DEM differencing was performed on grids with 1 m resolution (Fig. 5, f–h). To characterise topographic variations, vertical displacements were classified into two categories: uplift and subsidence. This analysis provides a clear contour map of displacements over time. Overall, the site exhibits progressive lowering, with the only notable elevation change occurring at the filled sinkhole.

Fig. 6 shows the sections used to compare topographic profiles over

the investigated time window. High-resolution DEMs (2.5 cm cell size) of the recently formed sinkholes SH1 and SH2 were generated from the September 2018 GPS survey, allowing detailed morphological analysis. For the same sinkholes, we also compared DEMs from July 2017 and September 2018 at 25 cm resolution. The profiles reveal that SH1 has nearly vertical cavity walls, whereas SH2 exhibits only one vertical wall. In SH1, the 2018 profile shows an altimetric variation of about 5 cm on the eastern rim and 30 cm at the bottom. In SH2, which exhibits evidence of reactivation, the profile indicates general subsidence, reaching 20 cm at the bottom, and a widening of the cavity. To further characterise the area, we traced two orthogonal sections across the plain: section EE' intersects the filled sinkhole, while section FF' crosses the central lowered area (Fig. 6).

Although the 2017–2018 interval is relatively short and cannot be considered representative of the full long-term evolution of the sinkhole system, it is useful for detecting recent local changes affecting already recognised sinkhole-related landforms. The longer-term component of the analysis is provided by the comparison with the 2008 LiDAR-derived DEM, which allows cumulative topographic changes over approximately one decade to be assessed. However, the morphological analysis does not provide a continuous deformation time series. Therefore, the observed ground changes cannot be used to determine whether subsidence occurred progressively, episodically, or in response to specific triggering factors such as intense rainfall, groundwater-level fluctuations, seasonal soil-moisture changes, or anthropogenic activities.

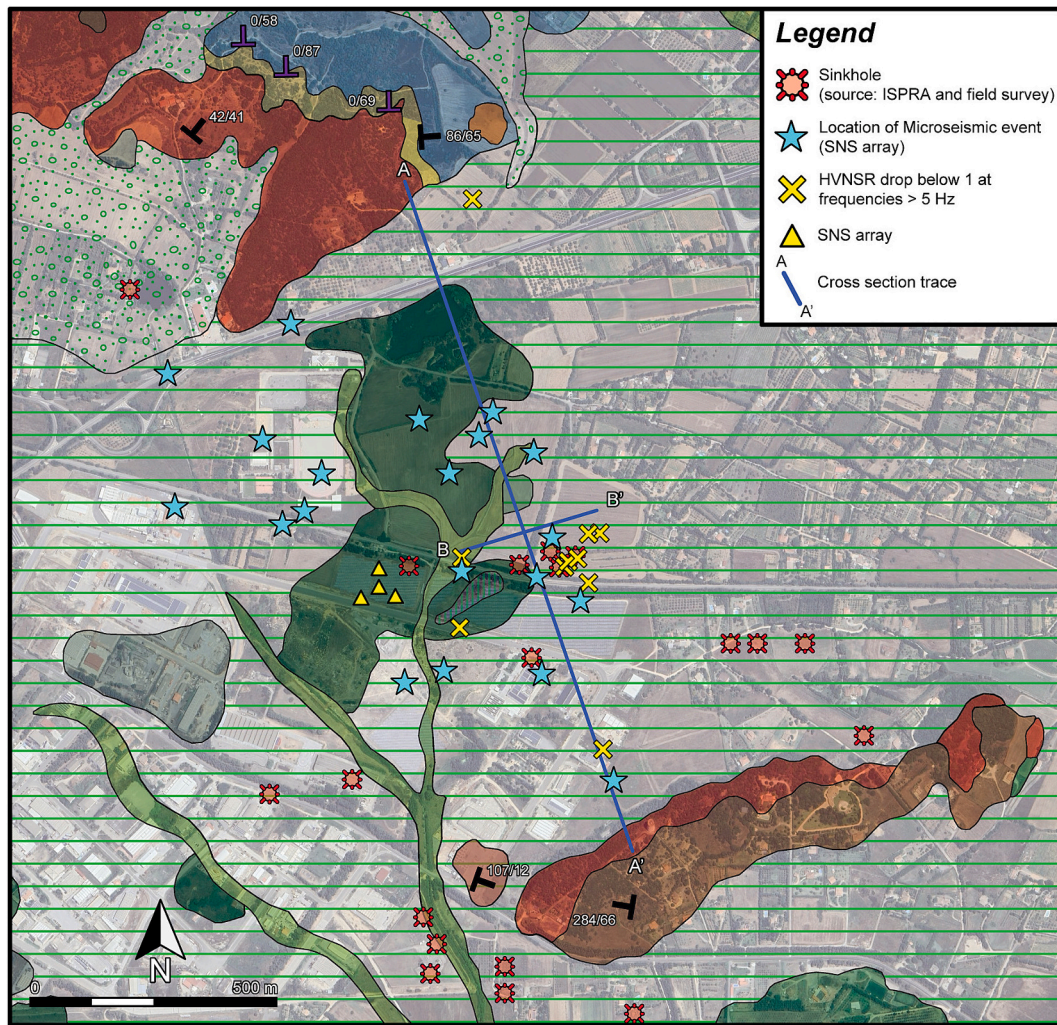


Fig. 4. Spatial distribution of the sinkholes that already occurred and clues of underground cavities by seismic ambient noise measurements and of rock mass deformation by SNS monitoring. It is noteworthy how signs of underground cavities and deformations cluster at specific points in the Cixerri Plain, particularly near areas where subsidence events have previously occurred.

5. Discussions

The engineering geological model of the subsurface in the Cixerri Plain was developed through geophysical interpretation of processed HVNSR seismic ambient noise measurements, microseismic signals recorded by the SNS array, and geomorphological surveys. This integrated dataset allows the subsurface architecture of the Cixerri Plain to be reframed as a fault-controlled buried-karst system rather than a laterally uniform alluvial cover over carbonate bedrock. HVNSR peak polarisation patterns delineate structural discontinuities consistent with a horst-and-graben framework, implying abrupt lateral changes in bedrock depth and, consequently, in cover thickness and stress distribution. This structural segmentation of the bedrock provides a geological explanation for the spatial clustering of: i) drops in the HVNSR function reveal a deamplification which is compatible with seismic velocity inversions or stiffness reductions that might be interpreted as proxies for partially voided horizons, ii) nanoseismic microevents attributed to microcracking within the bedrock, and iii) localised subsidence revealed by DEM differencing analysis. The coexistence of these independent indicators supports an active evolutionary scenario in which fault zones focus groundwater circulation and may enhance mechanical degradation and cavity growth at or near the bedrock–cover interface, promoting the upward propagation of weakened or voided horizons through ravelling and/or piping, depending on cover thickness.

For these reasons, the integrated approach was used to identify sectors where subsurface cavity development may occur before surface evidence of collapses and sinkholes. In fact, sinkhole development is often a long-lasting, silent, and essentially invisible subsurface process that can remain undetected for years before manifesting abruptly at the surface.

In the Cixerri Plain, resonant soft soil, composed of Cixerri Formation sediments, creates a significant contrast in seismic wave velocity relative to the underlying Gonnese Formation bedrock. Interpretation of geophysical data led to the following considerations: (i) the Cixerri Formation deposits locally exceed 15 m in thickness, consistent with findings by [Balía et al. \(2001\)](#); (ii) the seismic velocity contrast is more pronounced between the alluvial deposits (V_p ranging from 400 to 800 m/s) and the Cixerri Formation (V_p ranging from 2600 to 3100 m/s) than between the Cixerri Formation and the bedrock (Gonnese Formation, V_p exceeding 3400 m/s). The velocity values presented here are based on results from previous geophysical investigations conducted by [Balía et al. \(2001\)](#). Such pronounced impedance contrasts make ambient seismic noise measurements suitable for reconstructing subsurface geological structures and screening areas where cavity-related surface effects may occur.

Based on the defined geological model, reference cross-sections have been reconstructed ([Fig. 7](#)) along the A-A' and B-B' traces shown in [Fig. 1](#). The model is constrained by HVNSR measurements, which reveal two resonance peaks. The first peak is associated with the contact

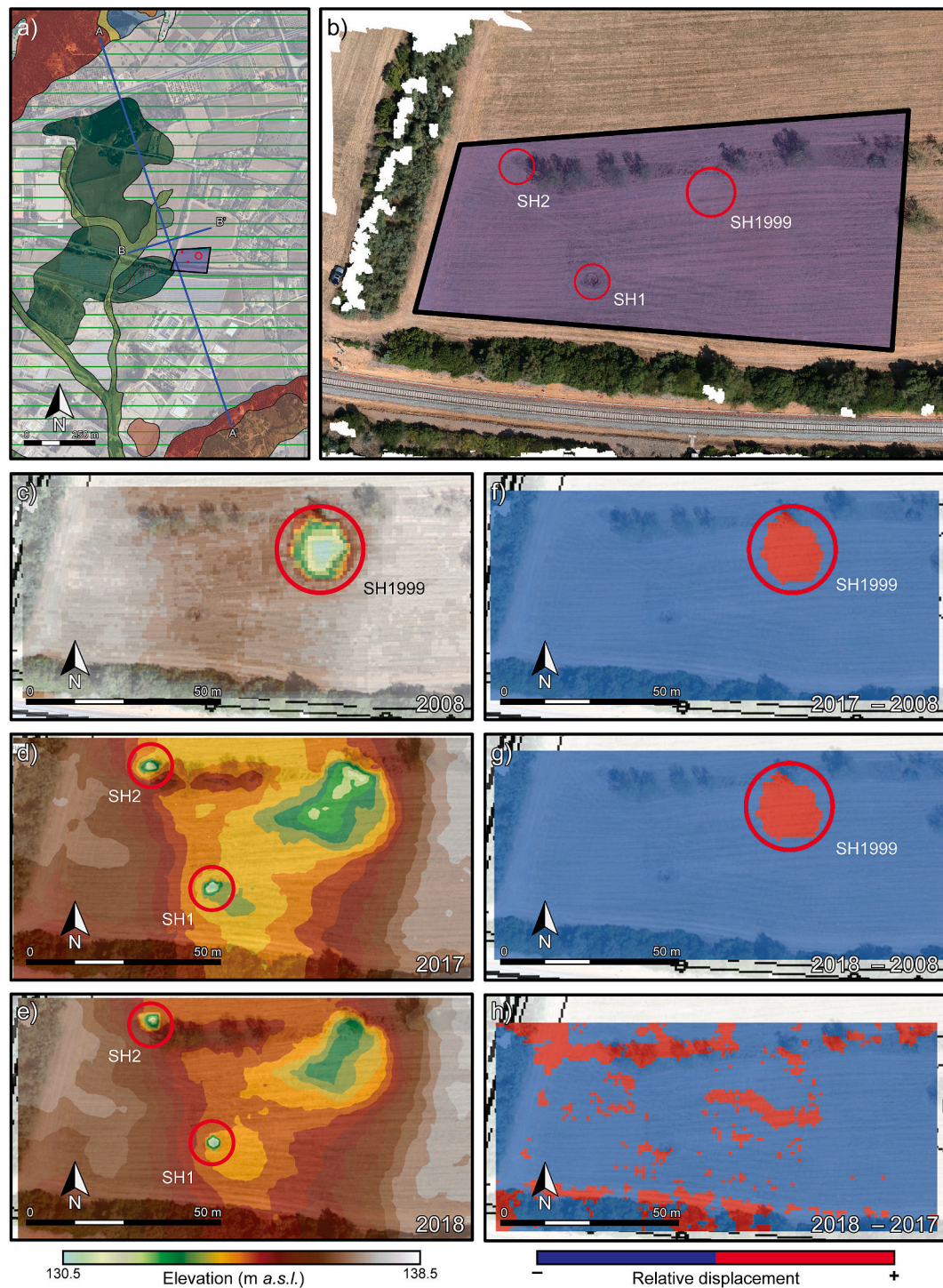


Fig. 5. (a) Map of the study area shows the extent of the topographic surveys, reported with the blue box, and the sinkholes, reported by red circles (for the geological information, refer to Fig. 1). (b) Zoom of the extent of the topographic surveys over the orthophotography taken by drone. DEMs of the study area relating to 2008 (c), 2017 (d), and 2018 (e), from LiDAR flight (c) and GPS surveys (d and e). DEM difference maps showing relative displacement over the years: 2017–2008 (f); 2018–2008 (g); 2018–2017 (h). By subtracting the oldest DEM from the most recent each time, negative values are obtained for cells that have moved from higher to lower elevations, and vice versa. In this case, the results were characterised by blue (–) and red (+) colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between the bedrock and the Cixerri Formation, while the second peak corresponds to the contact between the alluvial deposits and the Cixerri Formation. The reconstructed sections indicate that, within the plain sector between the two Palaeozoic basement outcrops (Gonnesa Formation), which emerge at both ends of section A-A', HVNSR measurements allow for a depth estimate. Furthermore, in the A-A' cross-section

(Fig. 7a), the observed azimuthal directional effects of the first resonance peak in some HVNSR measurements can be attributed to a basement segmented into horsts and grabens by Pliocene faults, with displacements ranging from 40 to 80 m, consistent with findings by Funedda et al. (2009). These faults cut through both the geological bedrock and the Cixerri Formation and are subsequently sealed by

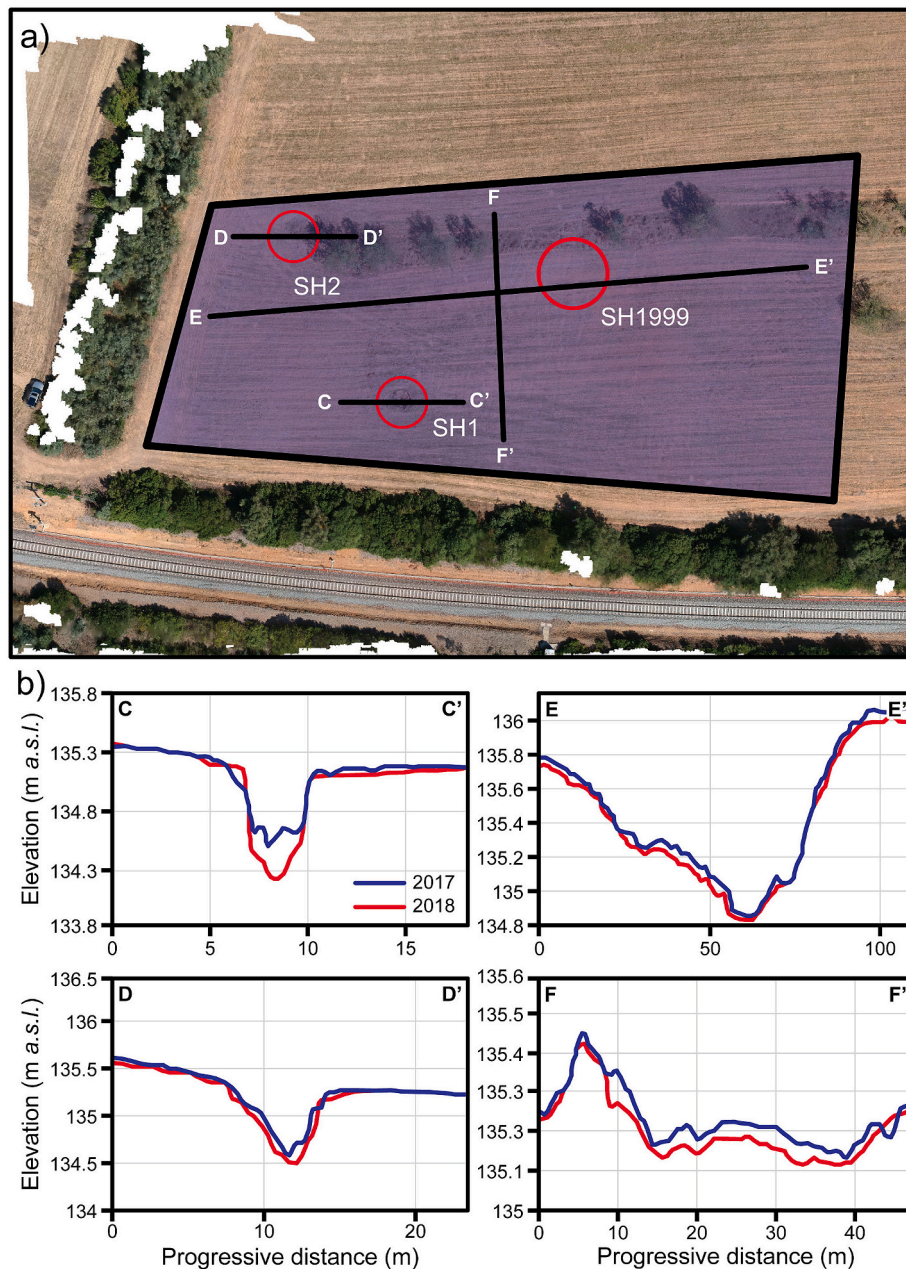


Fig. 6. (a) Extent of the topographic surveys (see Fig. 5a for the location of the box inside the study area) over orthophoto taken by drone, sinkholes (red circles) and topographic profiles (black lines). (b) Comparison between the morphological profiles of sinkhole SH1, C-C', calculated from GPS survey data for July 2017 and April 2018; vertical exaggeration factor: 10 $\times$. Comparison between the morphological profiles of sinkhole SH2, D-D', calculated from GPS survey data for July 2017 and April 2018; vertical exaggeration factor: 10 $\times$. Comparison between topographic profiles traced along the section E-E' for July 2017 and April 2018; vertical exaggeration: 80 $\times$. Comparison between topographic profiles traced along the section F-F' for July 2017 and April 2018; vertical exaggeration: 80 $\times$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pleistocene and Holocene deposits (Fig. 7). In particular, the NW-SE-oriented fault corresponds to a tectonic feature previously identified by Balia et al. (2001). In this context, the azimuthal directional effects of the HVNSR peak are attributed to near-surface scatterers that preferentially direct ground motion, thereby producing a 2D resonance model near fault zones. Conversely, where HVNSR peaks lack azimuthal directional effects, simple stratigraphic resonance conditions prevail, corresponding to a strictly 1D resonance model (depth-controlled model, as described by Kleinbrod et al., 2019 and Martino, 2024). To better visualise the geometry and setting of buried bedrock, where sinkholes have historically been recorded, section B-B' was reconstructed orthogonal to A-A' (Fig. 7b). As in the A-A' cross-section, fault

orientations were plotted based on the azimuthal directional effects of the HVNSR peak. Faults were traced such that the azimuthal directional effects of the HVNSR peak are observed to the SW and SE, indicating a 2D resonance model, where ground discontinuities act as seismic wave reflectors and diffraction sources (Burjáněk et al., 2010). The reconstructed geological sections indicate that Cixerri Formation sediments reach their maximum thickness in the central area between the two outcrops of the Palaeozoic basement. Given the presence of superficial alluvial deposits, the maximum thickness reaches approximately 90 m, in agreement with Funedda et al. (2009).

It should be noted that no new borehole data or additional direct geophysical investigations, such as electrical resistivity tomography,

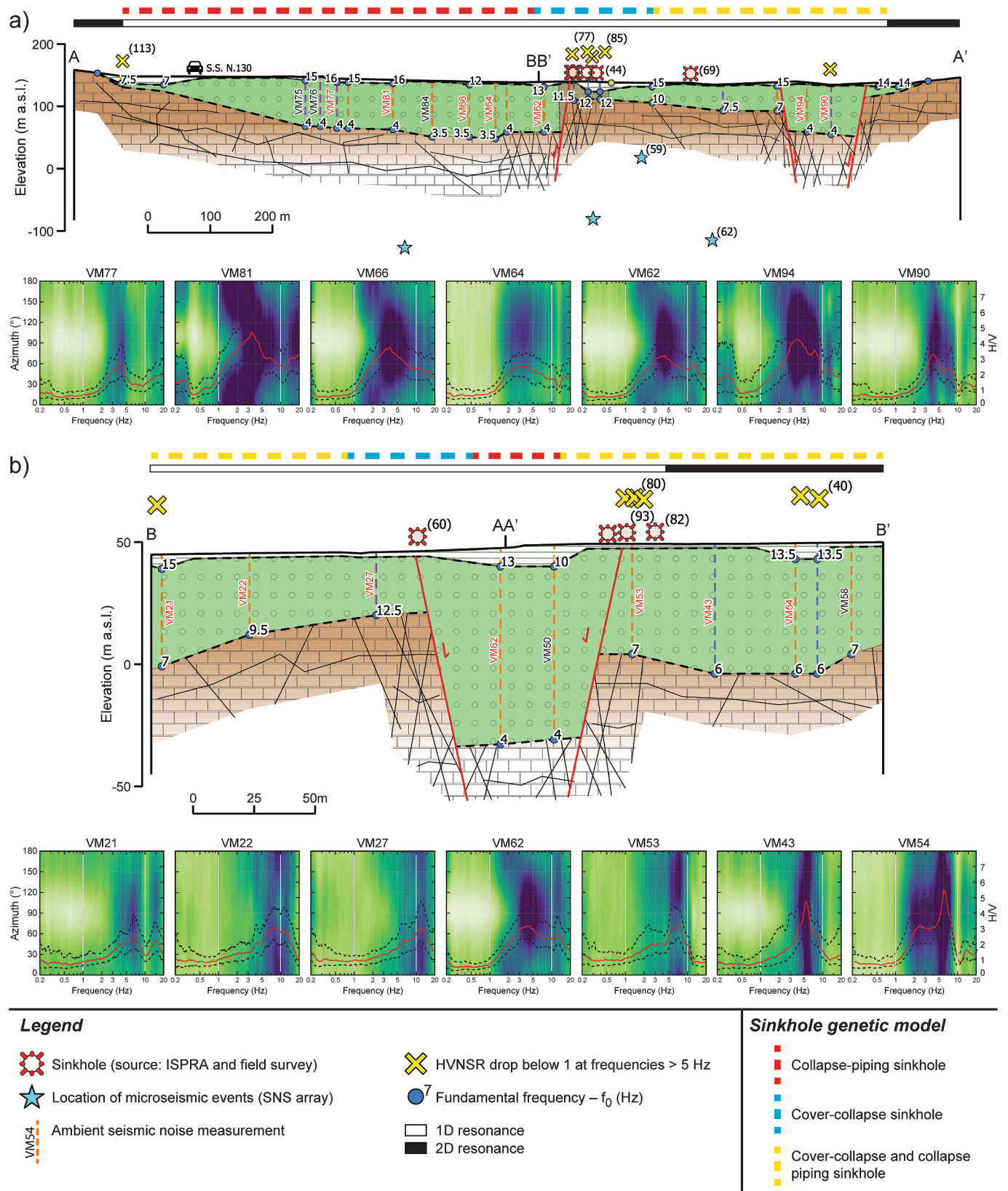


Fig. 7. Geological cross-section of the Cixerri Plain reconstructed after the multi-approach field investigations and based on the previously available materials: A-A ' (a) and B-B' (b). For each section, the results of the main seismic ambient noise measurements are reported in terms of the HVNSR function and its azimuthal directivity. The numbers in brackets indicate the projection distance, in metres, of these data in the section. At the same time, the proposed genetic model is reported along the chainage on the top of both sections, along with the type of resonance. For the legend of the lithologies and the location of the sections in the plan, please refer to Fig. 1.

microgravity, or active seismic surveys, were available to strengthen the model presented here. Therefore, the proposed subsurface model should not be regarded as a quantitative reconstruction of the depth, size, or geometry of individual cavities. Instead, it represents a process-based engineering geological interpretation aimed at identifying sectors prone to sinkhole development by integrating independent but indirect proxies. An external constraint is provided by the previous study of [Balía et al. \(2001\)](#), which investigated a more limited sector of the Cixerri Plain using borehole data and seismic reflection and refraction surveys. In the sector where their geological-geophysical sections and the sections reconstructed in the present study are approximately comparable, the main bedrock-cover geometry inferred from HVNSR data is consistent with the subsurface setting reported by [Balía et al. \(2001\)](#). This comparison supports the reliability of the first-order engineering geological model adopted here, particularly with respect to the depth variability of the carbonate bedrock and the role of structural discontinuities.

Building on the first observations by [De Waele and Muntoni \(2001\)](#) and [Ardau et al. \(2005, 2007\)](#), cover-collapse is suggested as the most likely mechanism for sinkhole development, due to the presence of a horst-and-graben structure. However, refining their initial observations using the detailed engineering geological model developed in this study, three hypotheses can be adopted as a conceptual model for sinkhole genesis in the study area, as shown in [Fig. 8](#).

In areas where seismic ambient noise measurements yield resonance frequencies above 7.5 Hz, indicating shallow bedrock, the most appropriate model for sinkhole genesis is the cover-collapse model. Cover-

collapse sinkholes are typically associated with relatively shallow bedrock (i.e., a thin sedimentary cover), where progressive void growth at the bedrock-cover interface is temporarily bridged by the overburden until the roof strength is exceeded, leading to an abrupt collapse at the ground surface. In this sector, several lines of evidence support a cover-collapse type. The fault network promotes intense bedrock fracturing and provides preferential pathways for groundwater circulation, thereby enhancing downward seepage and sediment removal by raveling: fine material can be progressively mobilised from the shallowest cover horizons and transported downward, leading to the formation of voids within the overburden even in the absence of a pre-existing hypogeal karst cavity. The fact that the shallowest bedrock occurs within the most topographically depressed portion of the study area further reinforces this interpretation, as this area likely acts as a local convergence zone for surface runoff, resulting in infiltration rates higher than in the surrounding plain. At the same time, the same fault system may also favour suffosion and piping processes, particularly under marked seasonal oscillations in soil moisture and in both shallow and confined groundwater levels, potentially accelerating void growth and predisposing the cover to sudden collapse. Notably, this sector combines several factors: (i) a shallow bedrock surface, (ii) a highly fractured and tectonised setting, and (iii) a likely surface-water accumulation zone promoting preferential infiltration; together, these conditions may constrain the observed elevation changes, with the recurrent multi-year lowering (down to 9 cm) plausibly reflecting a more generalised cover-subsidence behaviour conceptually related to cover-collapse mechanism but expressed over a broader area without discrete cavities, capable of

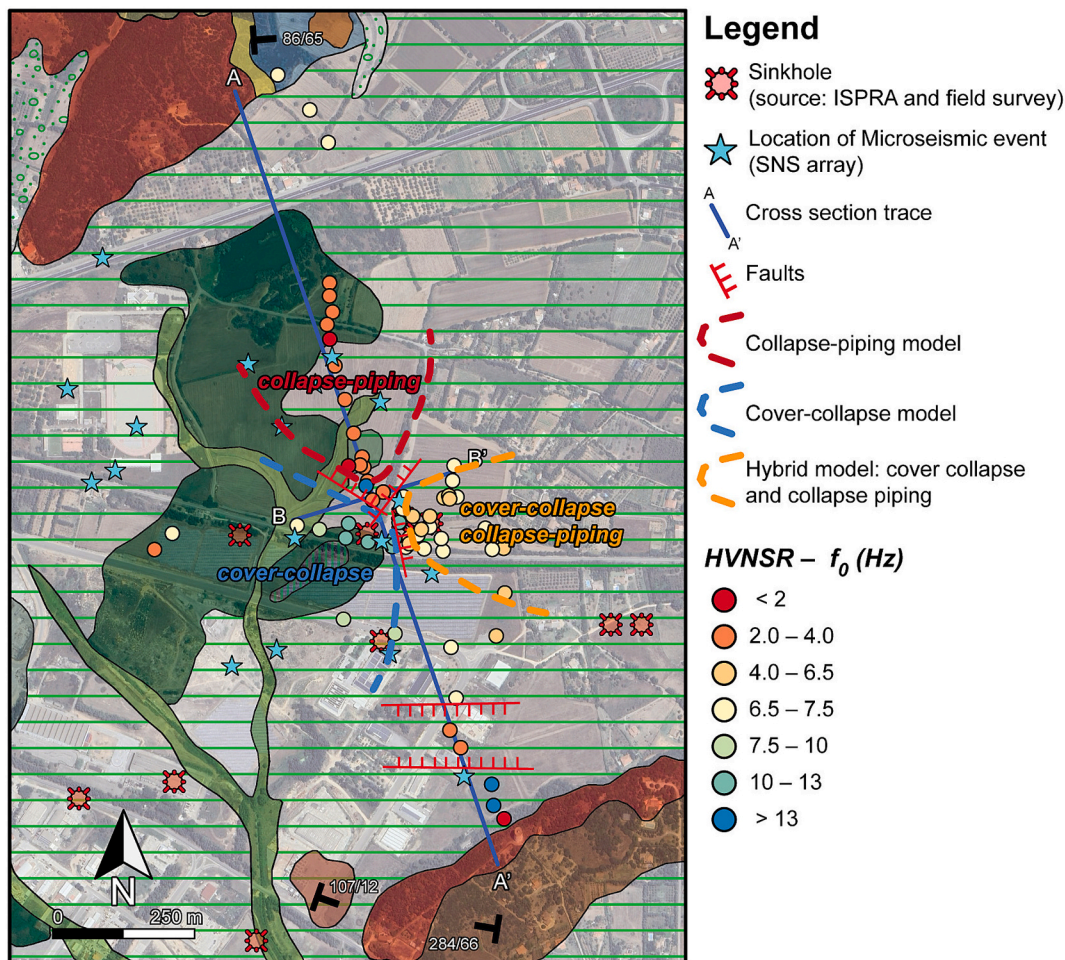


Fig. 8. Proposal for differentiation of the genetic process of sinkholes in the Cixerri Plain based on the geological model reconstructed using geophysical and morphological analysis results. The same proposal is also reported along the cross-sections in [Fig. 7](#).

generating larger depressed zones (up to 50–100 m or more) identified in the DEM analyses. On the contrary, in the sector where ambient seismic noise measurements return resonance frequencies below 4.0 Hz, suggesting the presence of a deep bedrock, the most appropriate model to explain sinkhole genesis is the collapse-piping. Collapse-piping sinkholes can develop where the bedrock is relatively deep and buried beneath a thick, unconsolidated cover, because sustained seepage and hydraulic gradients progressively remove fine particles (ravelling/suffosion) and generate an upward-migrating erosion pipe or voided chimney that may ultimately collapse when the overburden can no longer be supported. Lastly, in the third sector, where sinkholes have historically been recorded, the bedrock depth inferred from ambient seismic noise analysis, which yields resonance frequencies of approximately 4.0–7.5 Hz, suggests a hybrid evolutionary model that accounts for both cover-collapse and collapse-piping.

Where the bedrock is deeper, the same horst and graben structural architecture may instead promote collapse-piping through the predisposition by the fault- and fracture-controlled groundwater circulation, the preparation by the ravelling/suffosion-driven removal of soil material that progressively generates upward-migrating voids without requiring a pre-existing karst cavity, and triggered by the strong seasonal to event-scale fluctuations in soil moisture and groundwater levels in both shallow and confined aquifers detected in the study area, as already mentioned for the cover-collapse mechanism. However, the “deep” collapse-piping hypothesis *sensu* Nisio and Salvati (2004) should be invoked cautiously unless its key prerequisite (cold, mineralised waters with ascending gas and potential artesian behaviour; the “A/G factor”) is demonstrated, and it also requires a hydraulic connection between deep and shallow aquifers, considered unlikely by Atzeni et al. (1994) but potentially facilitated by local tectonisation (field evidence such as subcircular pools within small depressions therefore deserves targeted hydrogeochemical and hydrogeological investigation to constrain water provenance).

A hybrid cover-collapse to collapse-piping model (Caramanna et al., 2008) appears most consistent overall, especially in sectors in which bedrock tend to become deeper (e.g., the SE sector), because the fractured bedrock can host cavity growth and sediment evacuation at depth, while groundwater-level oscillations associated with intense rainfall and prolonged drought may episodically accelerate piping and destabilise the cover; importantly, the documented sinkholes are dry, arguing against “deep” collapse piping as the sole mechanism, and the nano-seismic dataset, composed of 20 microevents in two days that are comparable to high-risk sinkhole areas (Wust-Bloch and Joswig, 2006; Fiorucci et al., 2017; Iannucci et al., 2020a), indicates active micro-fracturing and likely cavity development within the bedrock, consistent with the hypothesis that expanding bedrock voids may reach the bedrock-cover interface, initiate proto-cavities, and then migrate upward through combined ravelling and piping until culminating in cover-collapse. Nonetheless, the relatively deep hypocentral depths of the macroseismic events (shallowest event at ~120 m, with a conservative uncertainty of ~40 m still yielding ~80 m) suggest that much of the detected seismicity is rooted in the bedrock rather than the sedimentary cover, complicating a purely cover-collapse interpretation and reinforcing a depth-dependent, hybrid evolutionary framework for sinkhole hazard in the Cixerri Plain.

The spatial distribution of HVNSR anomalies, expressed by sudden drops below unity, suggesting deamplification, is consistent with the depth-dependent framework. These anomalies cluster where shallow bedrock favours cover-collapse processes and become less frequent where the bedrock deepens, allowing collapse-piping to be dominant. This distribution supports the coexistence of both mechanisms. It also highlights the need for further hydrogeological and geophysical investigations to verify the origin of HVNSR anomalies and to better constrain the role of subsurface water flow in driving sinkhole evolution.

Fig. 9 provides a schematic representation of the adopted genetic-evolutionary model, summarising the key processes governing

sinkhole development in the study area.

Within the framework of the proposed evolutionary models, the sinkholes affecting the Cixerri Plain can be interpreted as the outcome of depth-dependent interactions among predisposing, preparatory, and triggering factors. Predisposing factors are represented by the inherited geological and morpho-structural setting, namely, laterally variable thicknesses of soft covers over a fractured (locally karstified) bedrock, which defines the intrinsic susceptibility of the system to deformation (Gunzburger et al., 2005; Fiorucci et al., 2020). Superimposed on this background, preparatory factors operate over medium to long time-scales and at low to moderate intensity, promoting the progressive accumulation of irreversible strain and moving the system toward failure: in shallow-bedrock sectors, rainfall-driven infiltration can initiate ravelling and suffosion within the upper cover horizons and enhance downward seepage along fracture networks, whereas in deeper-bedrock settings groundwater circulation may become dominant, and, if locally pressurised, may favour deep piping processes within tectonised zones. Finally, triggering factors act over short timescales and at moderate to high intensity and may be necessary and sufficient to initiate the deformative episode; in addition to intense rainfall events and rapid groundwater-level oscillations, anthropogenic actions, although not specifically addressed in this study, may contribute by perturbing the mechanical and hydrological equilibrium through vibrations and/or groundwater overexploitation, thereby acting as potential triggers for sinkhole activation.

The proposed approach and the resulting conceptual model should not be considered universally applicable to all karst settings, because the frequency thresholds, inferred bedrock depths, and geophysical signatures identified in the Cixerri Plain are site dependent. However, the general process-based framework may be transferred to buried-karst plains and intermontane basins characterised by: (i) soluble bedrock covered by continental deposits of variable thickness; (ii) a structurally controlled bedrock morphology; (iii) groundwater circulation focused along fractures and fault zones; and (iv) sinkhole mechanisms controlled by the interaction between cover thickness, sediment mechanical behaviour, and subsurface erosion processes. Comparable settings have been described in several Italian and international case studies. At Fossa San Vito-Sarno, southern Italy, cover-collapse sinkhole development has been related to a deeply buried carbonate bedrock and to subsurface erosion at the rockhead (Santo et al., 2019). In the San Vittorino Plain, central Italy, sinkhole distribution is strongly controlled by bedrock structure and hydrogeological conditions, with deep suffusion and deep piping processes linked to fluid circulation along fracture-fault systems (Centamore et al., 2009). The Acque Albule Tivoli-Guidonia area provides another relevant analogue, where cover-collapse and deep piping sinkholes occur in a complex structural and hydrogeological context (Argentieri et al., 2015; Billi et al., 2016). Similar principles also apply to alluvial-covered evaporite karst settings, such as the Ebro Valley in NE Spain, where sinkhole hazard assessment relies on identifying sinkhole mechanisms, inventories, and spatial relationships with geological and hydrogeological controlling factors (Gutiérrez et al., 2008; Galve et al., 2009).

Although the integrated dataset supports a coherent process-based interpretation of sinkhole development in the Cixerri Plain, some limitations must be acknowledged. The available datasets differ in spatial and temporal resolution: (i) HVNSR measurements provide point-based constraints that require geological interpolation, (ii) nanoseismic monitoring covers only a limited time window, and (iii) morphological differencing is based on a small number of surveys and does not represent a continuous deformation time series. In addition, the geophysical interpretation relies on simplified assumptions, including the adopted velocity model and the attribution of the main resonance peaks to key impedance contrasts. Similarly, sharp drops of the HVNSR function below unity are considered as a proxy of possible weakened or partially voided horizons, rather than direct evidence of open cavities. For these reasons, the proposed zoning should be regarded as a qualitative,

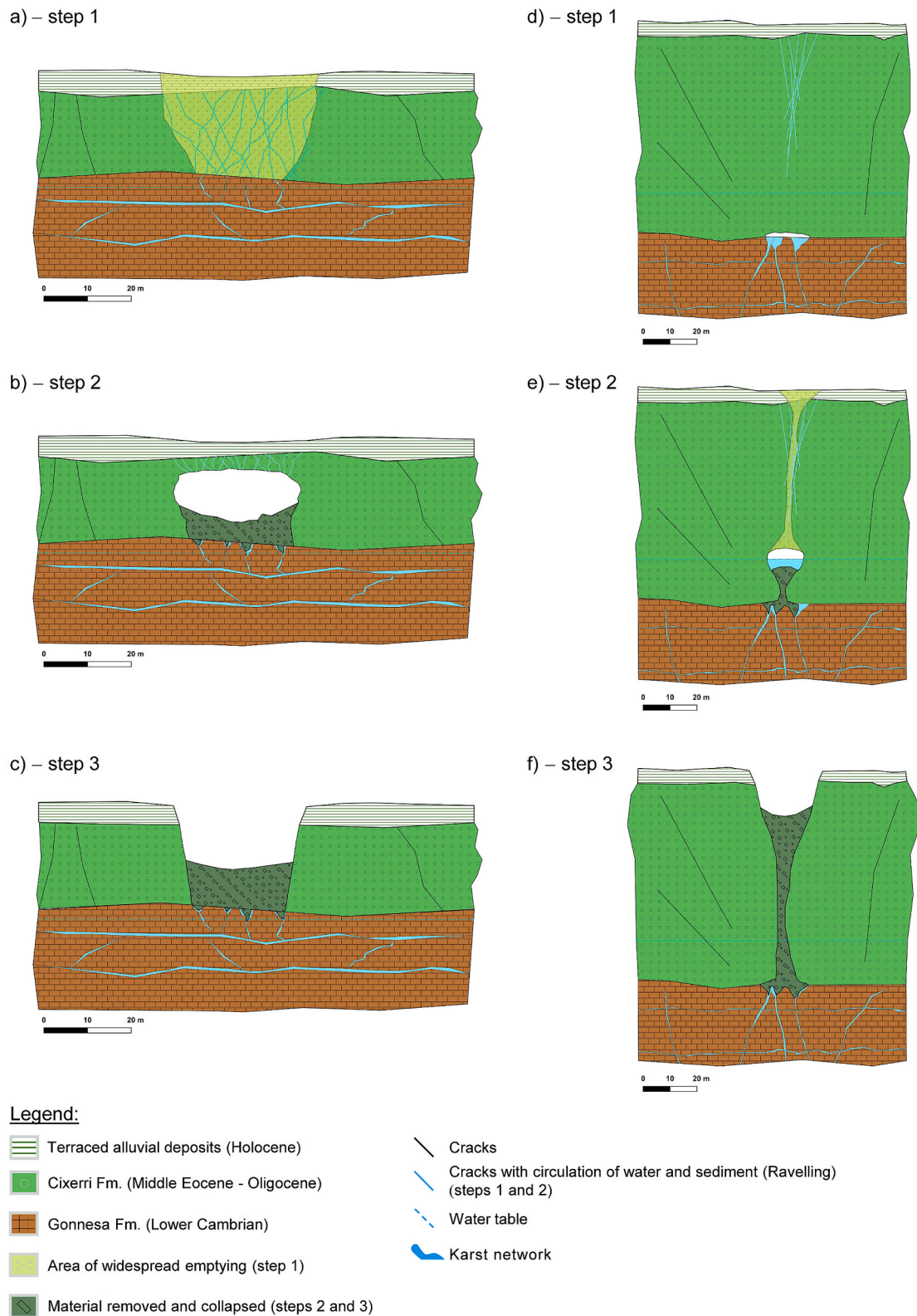


Fig. 9. Genetic-evolutionary model of *cover-collapse* sinkholes for the Cixerri Plain, on left: (a) initial condition of widespread “ravelling” without the presence of karst cavities in the bedrock near the interface with the covers (predisposition step); (b) progressive formation of the cavity in the covers (preparation step); (c) collapse of the vault of the cavity (triggering step). Genetic-evolutionary model of *collapse-piping* sinkholes for the same area, on right: (a) creation of the proto-cavity at the deep bedrock-cover interface due to piping phenomena (predisposition step); (b) upward migration of the cavity through the synergy of piping (from below) and ravelling (from above) (preparation step); (c) collapse of the vault of the cavity (triggering step). Both proposed models were taken by already published studies (Nisio, 2003; Waltham et al., 2005; Gutiérrez et al., 2007; Caramanna et al., 2008).

process-based framework for identifying sectors prone to sinkhole development, not as a quantitative reconstruction of individual cavity features.

6. Conclusions

This study aimed to assess the detectability of clues related to underground cavities, potentially evolving into sinkholes, through conventional (ambient seismic noise measurements) and innovative (nanoseismic monitoring) geophysical approaches, and to evaluate how predisposing subsurface conditions may promote their genesis and development, thereby adopting genetic–evolutionary models of sinkhole formation in the geological setting of the Cixerri Plain.

To address this goal, an engineering geological model was reconstructed by integrating previous data with new geophysical and topographical investigations. In particular, the near-surface geological framework was reconstructed from ambient seismic noise measurements, revealing a layer of continental sediments overlying a carbonate bedrock. The bedrock, modelled by Pliocene normal faults, exhibits a horst-and-graben geometry, with cover thicknesses reaching 80–120 m in some areas. These findings suggest that the cover-collapse sinkhole model (De Waele and Muntoni, 2001; Waltham et al., 2005; Gutiérrez et al., 2007) is applicable where the bedrock is shallow, whereas areas with thicker cover (>30 m) are predisposed to the collapse-piping model. The “deep” piping model is ruled out due to the absence of artesian conditions and gas upwelling, making the cover-collapse/collapse piping hybrid model (Caramanna et al., 2008) the most suitable in areas where transitions between horst and graben conditions occur in the subsurface.

The HVNSR function shows somewhere sudden spectral ratio drops (deamplification), indicating the probable presence of pre-existing underground cavities in the sector near existing sinkholes, suggesting depletion of the non-cohesive cover fraction, likely due to ravelling. The deamplification typically occurs in areas where sinkholes have historically opened, suggesting that seismic noise measurements could help identify areas prone to cover-collapse sinkholes.

Topographic analyses using GPS (2017 and 2018) surveys and LiDAR (2008) confirmed subsidence, particularly where sinkholes formed in 1999, 2008, and 2017. Two types of subsidence were identified: generalised subsidence across the plain and localised, concentrated deformation (~50–100 m) aligned NS in the study area, coinciding with seismic noise results anomalies (sudden drops below unity in the HVNSR function). This suggests a drainage process within sedimentary covers, reinforcing the collapse-piping model.

Based on these findings, cover-collapse and collapse-piping models are the most representative mechanisms in the study area to be considered to justify the development of sinkholes. A spatial zoning approach is proposed to distinguish ravelling-dominated from ravelling–piping combined processes. The results confirm that the Cixerri Plain is a high geological-risk area, consistent with other sinkhole-prone areas in Italy (Nisio and Salvati, 2004). These findings enhance current understanding and provide new insights into sinkhole characterisation and risk assessment.

From an engineering geology perspective, the key outcome is the definition of observable, field-applicable criteria for process-based zoning in sinkhole-prone plains: i) bedrock-depth proxies from HVNSR fundamental frequency, ii) cavity likelihood from sharp HVNSR amplitude drops resulting in a local deamplification, iii) activity state and location from clustered macroseismic events, and iv) subsidence from DEM differencing. Integrating these criteria reduces interpretative ambiguity and provides a decision-oriented workflow for prioritising monitoring and mitigation in thick-cover, fault-controlled karstified bedrock settings.

Future targeted boreholes and independent geophysical surveys would be required to validate the geometry of individual subsurface cavities and to refine and make quantitative the proposed hazard model.

Authors contribution

MF: Conceptualisation, Data curation, Field investigation, Methodology, Writing–original draft. GG: Methodology, Formal Analysis, Writing–original draft. NB: Formal Analysis, Field investigation. SM: Funding acquisition, Project administration, Supervision, Methodology, Writing–review and editing.

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CRediT authorship contribution statement

Matteo Fiorucci: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Guglielmo Grechi:** Writing – original draft, Methodology, Formal analysis. **Niccolò Belcecchi:** Investigation, Formal analysis. **Salvatore Martino:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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