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URBAN SINKHOLES AND IMPLICATIONS IN COASTAL CLIFF RETREAT

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EXTENDED ABSTRACT

I *sinkhole* rappresentano una delle manifestazioni di instabilità più complesse e pericolose a livello geomorfologico, in particolare in ambienti costieri dove la concentrazione di infrastrutture, insediamenti urbani e reti di servizio amplifica le conseguenze di eventi improvvisi di collasso del suolo. A differenza di altri processi gravitativi o di erosione superficiale, i *sinkhole* sono spesso caratterizzati da una dinamica rapida e da una limitata riconoscibilità dei segnali precursori, rendendo difficoltosa sia la previsione sia la gestione del rischio. Questo aspetto risulta particolarmente critico lungo le coste mediterranee, soggette a una crescente occupazione antropica e a un'intensificazione dei processi naturali legata ai cambiamenti climatici, quali l'aumento degli eventi meteorici estremi, l'innalzamento del livello del mare e l'accelerazione dell'arretramento della linea di costa. In letteratura si evince come la genesi dei *sinkhole* sia il risultato di una combinazione di fattori predisponenti e scatenanti, che variano significativamente in funzione del contesto geologico e strutturale. I processi di dissoluzione carsica, la presenza di discontinuità tettoniche e la dinamicità della falda giocano un ruolo dominante nello sviluppo di cavità sotterranee e nel successivo collasso delle coperture superficiali in contesti carbonatici. Tuttavia, i *sinkhole* possono svilupparsi anche in assenza di carsismo, come nel caso di ambienti vulcanici, dove l'instabilità è controllata anche dalla presenza di tunnel lavici e dal grado di fratturazione del substrato. In zone costiere tali meccanismi risultano ulteriormente condizionati dall'azione del moto ondoso. La Sicilia orientale costituisce un laboratorio naturale di eccezionale interesse, poiché ospita, in un'area geografica ristretta, sinkhole sviluppatisi in contesti geologici profondamente diversi, legati sia a successioni carbonatiche sia a prodotti vulcanici. Nel settore di Siracusa, lungo il margine costiero dell'Altopiano Ibleo, tali morfologie si sviluppano principalmente in relazione a successioni carbonatiche interessate da fenomeni di dissoluzione profonda, circolazione idrica sotterranea ed instabilità delle coperture terrigene che favoriscono collassi improvvisi. Al contrario, nel settore di Catania e del territorio vulcanico etneo, i *sinkhole* risultano legati ad altri processi, quali il collasso di tunnel lavici in un contesto caratterizzato da fratturazione vulcano-tettonica attiva, micro-sismicità e intensa interazione con i processi marini lungo la fascia costiera. Il presente lavoro analizza due casi studio rappresentativi di questi differenti contesti, selezionati lungo la costa di Siracusa e lungo il fronte costiero di Catania, con l'obiettivo di confrontare le caratteristiche morfologiche, le condizioni predisponenti ed i possibili meccanismi evolutivi dei *sinkhole* in funzione del quadro geologico di riferimento. L'analisi si basa su rilievi geomorfologici ad alta risoluzione ottenuti mediante fotogrammetria aerea, che hanno consentito una ricostruzione tridimensionale dettagliata delle geometrie di collasso, delle relazioni tra sinkhole e discontinuità strutturali e della loro connessione con le forme costiere adiacenti. Questo approccio consente non solo una descrizione morfologica accurata, ma anche una lettura in chiave evolutiva, evidenziando possibili scenari di arretramento della linea di costa e le interazioni con elementi naturali e infrastrutturali. I risultati forniscono elementi utili per la valutazione del rischio geomorfologico in aree ad elevata vulnerabilità e sottolineano l'importanza di strategie di pianificazione territoriale e di gestione del rischio che tengano conto della specificità geologica locale, soprattutto in contesti urbanizzati.

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ABSTRACT

The development of collapse sinkholes in urbanized coastal areas represents a serious threat to the safety of infrastructures and human settlements. Although this phenomenon is linked to natural coastal evolution processes, it poses a significant risk in densely urbanized settings. This study investigates two sinkholes that developed along the eastern coast of Sicily (Italy), in different geological settings. One occurs within a carbonate rock mass affected by karst processes and tectonics, whereas the other formed in a volcanic environment prone to intense fracturing and marked heterogeneity of the lava rocks. Aerial photogrammetric surveys were conducted to perform a digital rock mass analysis aimed at identifying the main discontinuities controlling the formation of these structures. The results highlight how lithological and structural differences govern sinkhole development, providing valuable insights for risk assessment and management of critical coastal areas.

Keywords: *sinkhole, photogrammetry, coastal retreat, urban hazard*

INTRODUCTION

Sinkholes represent one of the main forms of geological instability in coastal areas, posing a significant risk to densely urbanized environments and sensitive infrastructures. The sudden nature of these events and the lack of clear precursory signals make them particularly insidious, especially along shorelines characterized by high population density and the presence of water, sewage, road, and industrial networks (Margiotta *et alii*, 2021). Assessing the potential risk associated with sinkholes requires an integrated and multidisciplinary approach based on the combined analysis of geological, geomorphological, hydrogeological, and geophysical characteristics. Studies conducted in various Mediterranean contexts indicate that the genesis and evolution of coastal sinkholes depend on the complex interaction among soluble lithologies, groundwater dynamics, tectonic discontinuities, and coastal processes, as well as anthropogenic factors such as groundwater abstraction or vibrations induced by infrastructural activities (Basso *et alii*, 2013).

Lithological characteristics play a crucial role. For example, fractured carbonate sequences, evaporites, or dolomitic limestones may undergo deep dissolution, particularly when these lithologies are overlain by deformable terrigenous covers (Lima *et alii*, 2023). The presence of active faults or deep fracturing may also favour preferential drainage pathways that enhance both water circulation and development of subsurface cavities (Basso *et alii*, 2013; La Rosa *et alii*, 2018). Coastal hydrogeological dynamics represent an additional predisposing factor: rapid fluctuations in the water table, interactions between freshwater and seawater, and marine intrusions can compromise the stability of near-surface deposits (Liso, 2024). In these settings, seasonal oscillations, intense rainfall events, storm surges, and coastline retreat may intensify such processes, as demonstrated by recent studies on coastal sinkholes monitored through drone-based photogrammetric surveys (Busetti *et alii*, 2024).

While sinkholes are typical of carbonate settings and karst-prone areas, similar morphological features often develop in geologically distinct environments, leading to a remarkable variability in genetic conditions. Eastern Sicily is a prominent example, with sinkholes occurring through profoundly different geological settings.

On the carbonate successions of the Hyblean Plateau (southeastern Sicily), sinkholes mostly arise from karst–structural processes, including deep dissolution along tectonic lineaments, instability of overlying terrigenous covers, fluctuations in the groundwater table, and sudden collapses of karst cavity roofs (Ruggieri *et alii*, 2022). Moving northwards, the geological setting shifts to the Mount Etna volcanic environment, characterized by lava flows and pyroclastic deposits affected by a variable degree of fracturing and locally hosting lava tubes (Branca *et alii*, 2017). Here, sinkholes originate from either to the collapse of lava tubes or the instability of loose pyroclastic deposits, with susceptibility further enhanced by active faulting and microseismicity (Branca *et alii*, 2017; Azzaro *et alii*, 2020). In coastal sectors, the interaction of endogenous processes, marine dynamics, and human activities increases near-surface instability, while marine erosion of fractured lava platforms further promotes sinkhole development in lava tube–affected areas (Delle Rose *et alii*, 2004; Caramma *et alii*, 2008; Calvari *et alii*, 2024; Esposito *et alii*, 2018; Puzzilli *et alii*, 2024).

This paper examines two case studies that exemplify the dual genesis of sinkholes in different lithological settings. The first case involves a collapse that occurred along the coastal carbonate cliff of Siracusa, in proximity to a cycle path. The second case concerns a sinkhole that developed in the volcanic setting of Catania city, along the urban waterfront and in proximity to road and pedestrian infrastructures.

The aim of this study is to compare morphological features, evolutionary processes, and predisposing conditions of sinkholes in different geological contexts. Attention is paid to the possible sinkhole evolution and its influence on coastline retreat and the stability of adjacent natural and anthropogenic elements, with implications for land-use planning and geomorphological risk management in complex coastal settings. A high-resolution geomorphological analysis was carried out using Unmanned Aerial Vehicle (UAV)- based photogrammetry, which enables detailed characterization of sinkhole morphology and its relationship with surrounding landforms (Westoby *et alii*, 2012). This approach has been widely applied to studies of sinkholes and surface instability in karst, volcanic, and coastal environments (Özgür *et alii*, 2025; Michelena *et alii*, 2020), providing an effective framework for investigating rapidly evolving and partially inaccessible areas.

THE STUDY AREAS

Two urban areas located in eastern Sicily and affected by sinkhole occurrence were selected as case studies.

The first area is located along the coastline of the city of Siracusa (Figure 1a), where a sinkhole occurs a few tens of meters away from a pedestrian pathway. Siracusa city lies along the eastern margin of the Hyblean Plateau. From a structural perspective, this area represents an emerged portion of the Pelagian block, bounded by a system of normal faults with significant displacement, predominantly oriented NE–SW (Lentini *et alii*, 2014). These fault systems collectively display an en échelon arrangement with right-stepping overlaps (Hirn *et alii*, 1997; Bianca *et alii*, 1999). From a lithological standpoint, the area is characterized by predominantly Tertiary and Quaternary carbonate successions (Lentini *et alii*, 2014).

The second study area is located along the southeastern margin of Mount Etna within the city of Catania (Figure 1b), where a sinkhole developed a few meters away from a roadway, along the pedestrian seaside promenade. In this sector, a sequence of lava flows, attributed to Holocene eruptive events, crops out forming a compact plateau characterized by massive, columnar, and scoriaceous morphologies typical of subaerial cooling (Monaco *et alii*, 2000). The structural framework of the coastal lava sequences is defined by NNW–SSE and NE–SW-trending extensional lineaments, active during the Quaternary, which influence the fracturing, disarticulation, and differential erosion of the lava surfaces (Monaco *et alii*, 2000).

METHODOLOGICAL APPROACH

The methodological approach adopted in this study is based on the use of UAV platforms to carry out photogrammetric surveys aimed at achieving a comprehensive morphological and structural characterization of sinkholes developed in the study sites. Surveys were conducted using an EVO Dual Enterprise V3 drone equipped with high-precision sensors and an RTK module, ensuring excellent image quality, stable flight performance and real-time centimeter-level positional accuracy. On average, approximately 300 photographs were collected per area, with flight planning designed to maintain a constant ground distance and to ensure 70–80% image overlap in both longitudinal and transverse directions. The camera's optical axis was maintained within a 0–45° range to integrate nadiral and oblique images, thereby enhancing the quality of the three-dimensional reconstruction through improved acquisition of vertical and subvertical geometries. The acquired images were processed using the Structure-from-Motion (SfM) technique, an advanced photogrammetric approach that reconstructs the three-dimensional geometry of complex surfaces from two-dimensional images taken from multiple viewpoints. The SfM algorithm automatically identifies homologous points across photographs, computes the relative position and orientation of the camera for each shot, and reconstructs the spatial coordinates of points through an iterative, self-optimizing triangulation process (Westoby *et alii*, 2012).

This methodology enables the generation of high-resolution 3D models in the form of point clouds. Digital rock mass surveys were carried out on these models with the aim of measuring the orientation of the main discontinuities. This analysis was carried out at different scales: a general observation of the coastline morphology allowed identifying the main structural sets controlling the coastline evolution. Then, focusing to the digital outcrop scale, discontinuities were surveyed at selected rock mass portions, according to a subjective criterion. Collected discontinuity orientation data were validated through focused field measurement on selected outcrops.

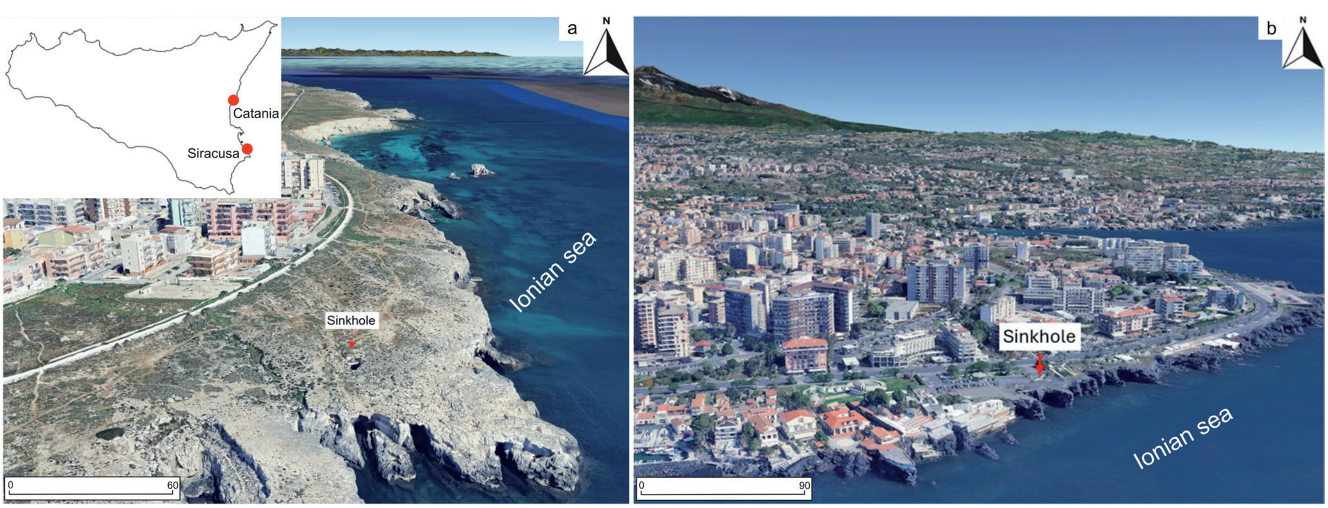

Fig. 1 - – Location of test sites: a) costal cliffs at Siracusa; b) costal cliff at Catania (Google Earth imagery)

RESULTS

The sinkhole of Siracusa case study

The sinkhole exhibits a sub-circular plan geometry, slightly elongated along the NNW-SSE direction, with an average diameter of approximately 7 m (Figure 2a). Morphologically, the sinkhole is characterized by sub-vertical walls and a concave, irregular floor, covered by accumulations of detrital material (heterometric blocks) resulting from both the main collapse and the subsequent failures of the marginal portions. The sinkhole rim is sharp and well-defined, which suggests a structural control on the occurrence of this morphological element. The generally regular and well-defined shape suggest a concentrated collapse mechanism compatible with the loss of support of the rock mass above an underground cavity. In fact, the dense point cloud reveals a spatial connection between the sinkhole and a sea cave with entrance located at the base of the coastal cliff (Figure 2 b-c). This cavity, shaped by the combined action of wave activity and dissolution processes, represents a key predisposing factor for the sinkhole formation. Progressive enlargement of the sea cave likely led to gradual weakening of the overlying rock mass, eventually exceeding equilibrium conditions and triggering the roof collapse.

The structural analysis of the dense point cloud allowed identifying four primary structural sets bordering the sinkhole, which are oriented N–S (D1), E–W (D2), NW–SE (D3), and NE–SW (D4) (Figure 2d). In particular, D1 and D2 show an orientation in space similar to the faults crossing the area, which control the coastal morphology (Figure 2e). This suggests a likely structural matching between local discontinuities and tectonic structures, implying that the former could be interpreted as secondary or derivative features genetically linked to the main fault systems.

The detailed digital rock mass survey was conducted along the sea cliff at the cave entrance (Figure 2f) by measuring the orientation of the main discontinuity planes in the dense point cloud. Six mains discontinuity sets were identified (Figure 2f). D1 and D2 are represented by planes sharing the same strike but often showing opposite dip directions. Specifically, D1 defines the orientation of the cavity's sub-vertical walls and likely represents the primary structural control on sinkhole development.

The D1–D2 system, which intersects at an angle of approximately 100°, is located within the collapse area, where it is crossed by the other discontinuity sets identified through the rock mass analysis. The interaction among these structural elements defines a likely weakness rock mass zone, setting conditions favorable for the collapse of the cavity roof. This specific structural condition may also constitute a predisposing factor for the instability of additional portions of the roof, both inland and seaward.

The Catania sinkhole

In plain view, Catania sinkhole displays an elliptical shape, with a major axis approximately 15 m long, oriented NE–SW, and a minor axis about 9 m long oriented NW–SE. It is located 16 m away from the coastline, where the entrance of two caves (A and B) was surveyed (Figure 3a). The sinkhole is part of the cave A system, which likely represents an old, NE-SW oriented, lava tube.

Within the sinkhole, the partially exposed roof of the lava tunnel consists of an intensely fractured layer of massive lava with an average thickness of approximately 1.5 m. Debris of anthropogenic origin (mainly concrete) and rock blocks partially obstructs the inland prosecution of the cave, making tough the estimation of the inland direction of the lava tube. The failure of the tube roof was likely enhanced by cyclic pressure fluctuations of air and water within fractures, induced by wave energy and fluid motion, which generate repeated stresses that promoted the progressive widening of microfractures. This mechanism led to a reduction in the strength of the roof and contributed to increasing instability until final collapse, resulting in the rapid formation of the surface depression.

The digital rock mass analysis carried out at the general scale allowed the identification of the main discontinuity sets shaping the coastline. Four sets were recognized, oriented approximately NE–SW (J1), NW–SE (J2), NNW–SSE (J3), and W–E (J4), together with a sub-horizontal set (J5). The intersection of these sets coincides with the area where the sinkhole developed, suggesting that its location is structurally controlled.

At a higher level of detail, analysis of the discontinuity sets at the roof of both caves revealed a pole distribution organized into several clusters (Figure 3b-c). Most of the clusters are consistent with the structural patterns observed at the general scale. Other clusters, however, appear to result from more localized processes, such as lava cooling. In particular, thermal contraction during cooling can produce radial or fan-shaped fractures, especially where the flow changes in thickness or at advancing lava fronts. These secondary features therefore reflect the emplacement and cooling dynamics of the lava and are most clearly visible at finer scales of analysis.

Joint sets J1 and J2 are particularly significant. J1 is aligned with the main axis of the Cave A, whereas J2 corresponds to a direction consistent with Cave B.

DISCUSSIONS AND CONCLUSIONS

This study analysed two coastal sinkholes located in the areas of Siracusa and Catania, with the aim of understanding the geological, structural, and morphological factors controlling their formation and evolution. In both cases, the results indicate that sinkhole development cannot be attributed to a single factor but rather arises from the interaction between the lithological predisposition of the rock mass and a pronounced structural control, which facilitated the onset of instability conditions and the subsequent collapse of subsurface cavities.

With reference to the Siracusa sinkhole, the discontinuities

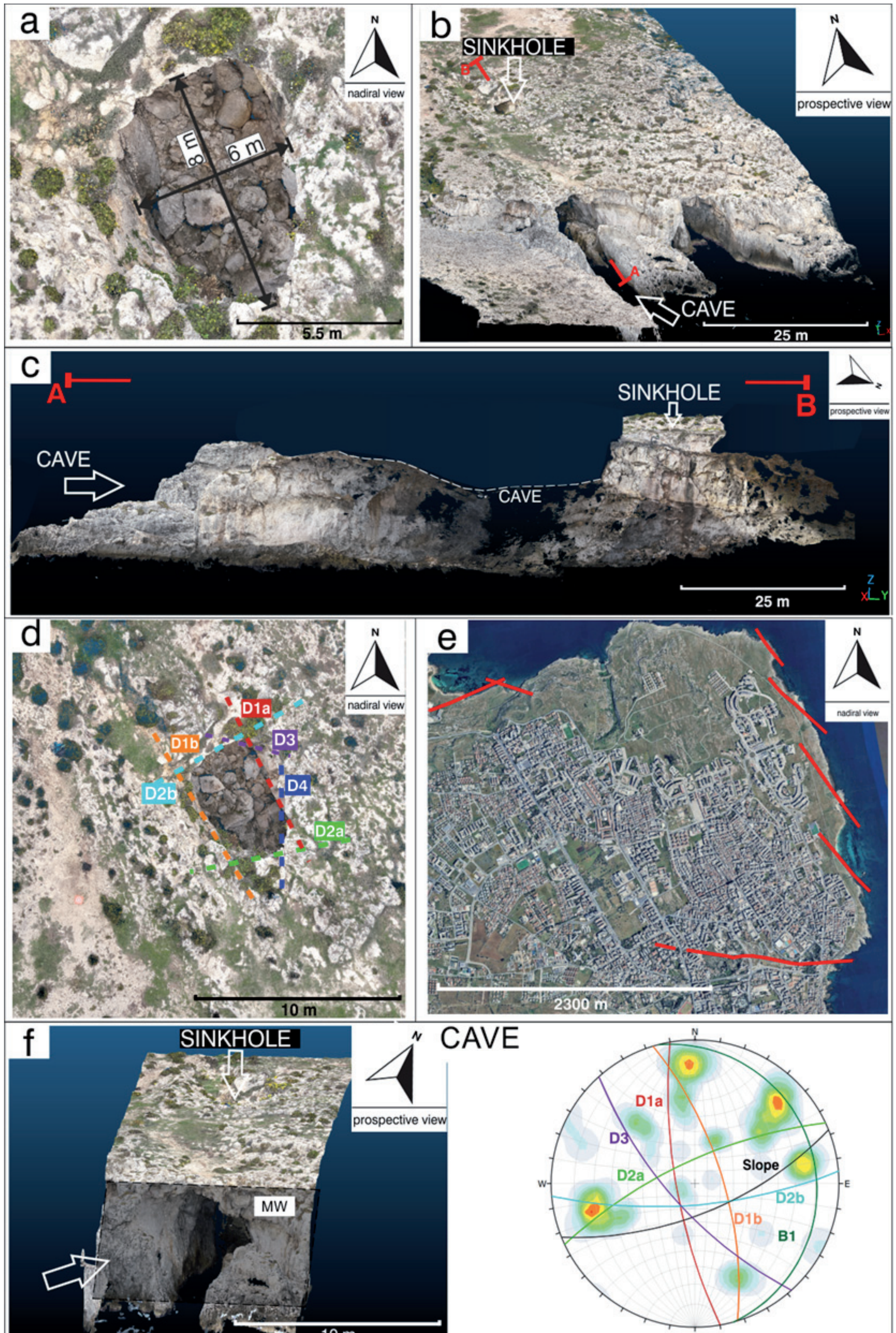

Fig. 2 - Case study of Siracusa: a) Morphometric analysis of sinkhole; b) dense point cloud of the study area; c) Cross-section showing the connection between the sinkhole and the adjacent marine cave; d) surveyed discontinuity planes bordering the sinkhole; e) overview of the main faults (Grasso et alii, 1987); f) stereoplot summarizing the results of the digital rock mass analysis (MW: measurement window for digital rock mass survey)

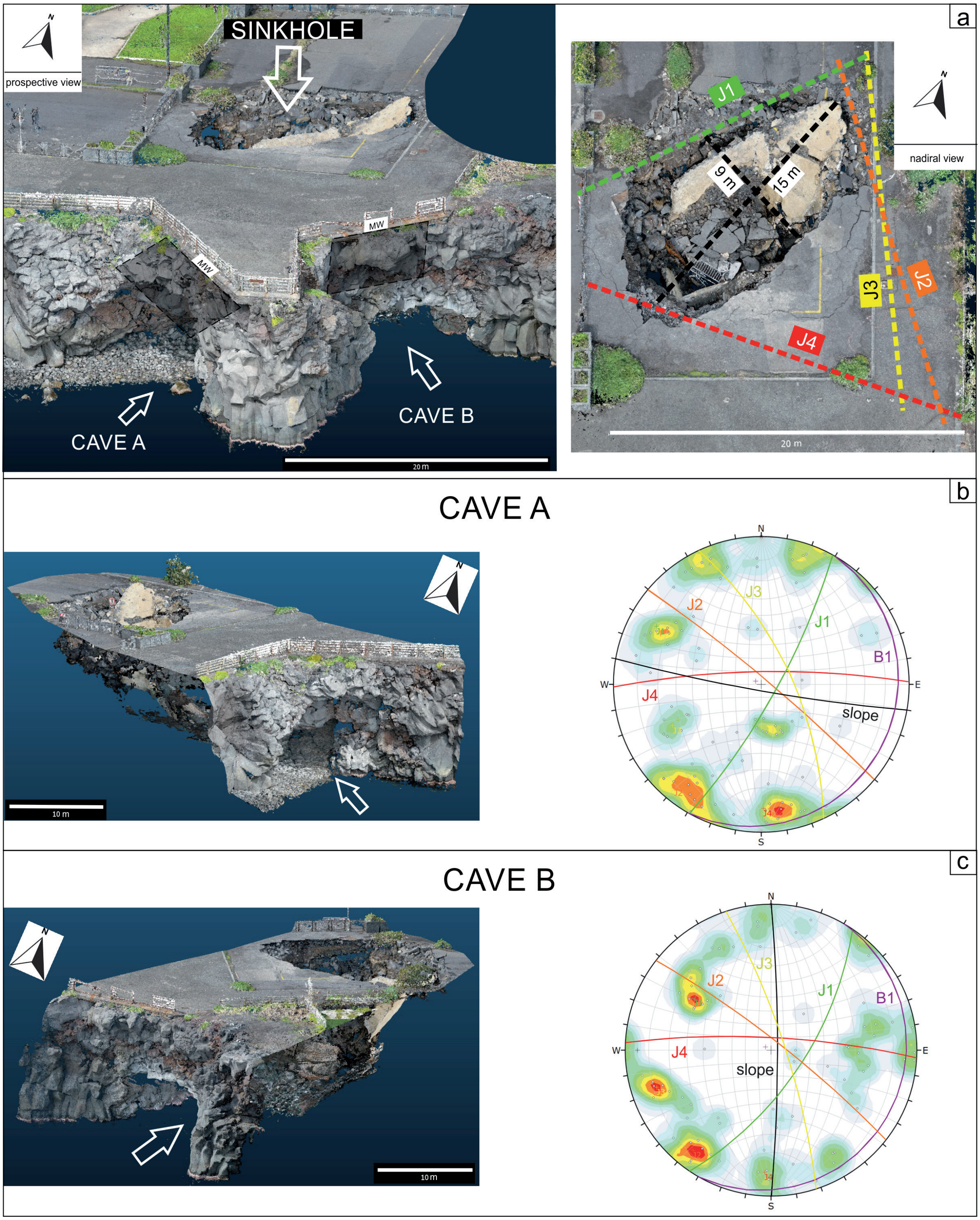

Fig. 3 - Case study of Catania: a) dense point cloud of the study area with indication of the structural discontinuities bordering the sinkhole (MW: measurement window for digital rock mass survey); b) Results of digital rock mass analysis of cave A; c) Results of digital rock mass analysis of cave B

surveyed are closely related to the local tectonics, aligning with the orientation of faults in the area, and appear to have significantly influenced the propagation of collapse and the formation of the sinkhole. The preparatory factor is the karst process affecting the local lithologies, which progressively weakens the substrate and promotes the formation of subsurface cavities. Given the structural configuration of the cavity and the sinkhole, it is likely that the morphological evolution of this coastline sector evolution involves progressive roof collapses, both in inland and seawards. Indeed, the formation of sinkholes can represent one of the initial stages of coastal morphological evolution, serving as an intermediate point in the cycle of instability that leads to the retreat of the coastline. Similar studies (Basso *et alii*, 2013; Flor Blanco *et alii*, 2022) highlight how the fracture network and local lithological conditions directly influence the propagation of collapses and the formation of cavities, contributing to the shaping of coastal morphology. These processes generate a recurrent cycle of collapse and readjustment of the coastal profile, with the continuous formation of new cavities and the development of erosion features typical of carbonate coasts, such as sea caves, natural arches, and stacks, which represent advanced stages of the morphological evolution of the coastal sector (Basso *et alii*, 2013; Flor Blanco *et alii*, 2022).

The Catania sinkhole is also controlled by the interaction of geological and structural factors. Photogrammetric surveys and point cloud analysis revealed that the rock mass is characterized by alternating massive sections and scoriaceous layers. The sinkhole developed along the roof of a lava tube at a critical intersection of the main joint sets that shape the coastal morphology. The morphological expression of this lava tube along the coastal cliff is represented by the presence of two adjacent cavities, while its continuation inland is currently unknown due to the obstruction by detrital material accumulated within the cavity. However, the main alignment along the tunnel suggests the need for further investigation, including indirect surveys, to verify its potential continuation beneath the urbanized area and determine its direction and extent. The high lithological and structural heterogeneity of the Etnean volcanic successions makes the identification of areas most prone to future morphological evolution complex and difficult to predict. The Mediterranean region, within which the Catania coastline is located, has experienced over the last decade an increase in the frequency and intensity of extreme marine–meteorological events, such as medicanes (Borzì *et alii*, 2024). In this context, the Catania coast is characterized by high geomorphological dynamism, which promotes widespread instability processes and pronounced coastal retreat, as demonstrated by Young *et alii* (2009), who showed that areas exposed to frequent wave impacts experience higher rates of marine cliff erosion.

Ongoing erosion is evidenced by the presence along the coastline of landforms typical of coastal retreat, such as sea caves and headlands; in particular, the headland located between two adjacent caves exhibits a morphological evolution consistent with their potential coalescence and the subsequent formation of an arch, which may ultimately evolve into an isolated stack. Such morphologies are already widespread along the Catania coast, indicating an advanced stage of erosional processes and a consequent landward retreat of the coastline.

The lithological context represents a necessary condition for the genesis of underground cavities, as both karst dissolution processes and the textural and structural heterogeneity of lava flows constitute preparatory factors for the formation of subsurface voids. However, the comparison between the two case studies highlights that these conditions, although essential, are not sufficient on their own to explain the localization and evolution of collapse morphologies. In both settings, structural control emerges as the common and dominant factor, since the interaction among the observed discontinuity systems leads to the development of zones of weakness that govern collapse propagation and constrain its geometry. When this structural framework is combined with the presence of underground cavities linked to specific lithological peculiarities, the system may reach conditions close to failure, significantly influencing coastal retreat and the subsequent evolution of the coastal sector.

This highlights the importance of developing interpretative and predictive models tailored to the specific geological context, which are particularly relevant for territorial planning and risk management in urbanized areas.

From the methodological point of view, results achieved by this study confirm that aerial photogrammetry is a valuable tool for the analysis of these geomorphological features, allowing the precise reconstruction of cavity geometries and collapse surfaces and facilitating the analysis of relationships between morphology, geological structures, and evolutionary processes.

In particular, the ability to quantitatively analyze the geometry of discontinuities along high and otherwise inaccessible coastal cliffs allows for a significantly more comprehensive understanding of the structural framework. This approach is consistent with numerous studies demonstrating that UAV photogrammetry is a highly effective tool for achieving high levels of detail in areas that are difficult to access and/or subject to protection constraints (*e.g.*, Caliò *et alii*, 2023; Mineo *et alii*, 2024a, b).

However, in surveys of this type, it is necessary to consider that data obtained through close-distance survey techniques must still be validated by direct field measurements, despite the high accuracy ensured by proper georeferencing of the images. Such validation is essential because additional expert-based verification can allow the identification of peculiar structural elements that may be missed when relying exclusively on UAV-derived data. A notable example is represented by sub-horizontal discontinuity planes, which are often underrepresented in statistically significant terms within datasets derived from photogrammetry and may therefore be classified as random discontinuities rather than true discontinuity families (Mineo *et alii*, 2025). In these contexts, these planes play a key role in collapse mechanisms, particularly in the failure of underground cavity roofs, directly influencing the overall stability of the system.

These results provide a robust basis for geomechanical hazard assessment and for the development of numerical and conceptual models aimed at evaluating the stability of coastal sectors.

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