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Development of methodologies and protocols for the analysis of the geotechnical and structural safety of archaeological monuments from the pre-Nuragic age in Sardinia

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ABSTRACT

Within the framework of the nomination for UNESCO recognition of the serial site '*Funerary Tradition in the Prehistory of Sardinia – The domus de janas*', a detailed analytical study was carried out on the monumental sites included in the nomination list.

The *Domus de Janas* (meaning 'House of the Fairies' in Sardinian) are unique rock-hewn tombs found across Sardinia. These ancient monuments often have several decorated rooms featuring paintings, engravings or bas-relief and were built between 3400 and 2700 BC, placing them in the late Neolithic to early Bronze Age periods.

The study included the geological survey, the identification of critical geotechnical issues, the analysis of the materials, the identification of the forms of decay and degradation taking place on the surfaces, the assessment of the stability of the artefacts and the risk levels arising from factors or events of natural or anthropogenic origin that could affect the conservation of the site. The assessments were carried out following a surveying campaign, the qualitative study of the cracking pattern, the assessment of any geotechnical and structural instability conditions at the monument scale, and hydrogeological instability conditions at the site scale. The data were systematised with the identification of risk categories, leading to a classification of the importance level of the sites according to a multi-risk approach. This paper illustrates the methodological process adopted and provides an overall view of the consistency of the monuments included in the UNESCO list, considering the results obtained through the critical interpretation of the data collected.

Keywords: Multi-risk Classification, Rock-hewn Tombs, Prehistoric Monuments, Stability Assessment, Material Degradation, Site Conservation.

INTRODUCTION

The 'Domus de Janas' (Fairy Houses) are hypogeal burial sites and necropolises located in Sardinia (Italy). They were created between the 5th and 3rd millennia BCE (Lilliu,1988). These rock-cut tombs feature complex layouts, symbolic decorations and figurative motifs (Figure 1) (Melis, 2014). They represent the most extensive and richest manifestation of hypogeal funerary architecture in the western Mediterranean (Tanda & Usai, 2005) and exemplify a phenomenon attested by around 3,500 tombs spread across the entire island.

In July 2025, some of the most significant tombs were added to the UNESCO heritage list under the title 'Funerary Tradition in the Prehistory of Sardinia – The Domus de Janas' (UNESCO World Heritage Centre, 2023). Figure 2 shows the list of sites included in the UNESCO heritage represented on the lithology map of Sardinia. This serial site is an extraordinarily well-preserved example, striking an exceptional balance between historical artefacts and the natural environment that has evolved over millennia. Therefore, special attention has been paid to studying the material aspects and assessing the monuments' integrity in terms of surface preservation, structural safety, and landscape integrity.

Figure 1. *Necropolis of "Sa Pala Larga", Bonorva (SS) (left). Necropolis of "Montessu", Villaperuccio (SI) (right).*

For this reason, an analytical procedure has been developed to evaluate the state of conservation of the necropolises. The analytical study involved a thorough evaluation of all sites using a variety of methodologies, including geological surveys and identifying critical geotechnical issues. It also involved analysing materials and identifying forms of decay and degradation on surfaces. Furthermore, integral components of the study were the structural characterisation of architectural components and the assessment of artefact stability. Finally, risk levels arising from natural or human-made factors or events that could affect the site's conservation were assessed.
The assessment process was initiated following a surveying campaign involving the following actions:

1) in situ surveys, including the collection of a small number of samples for mineralogical and petrographic analysis;
2) qualitative analysis of the cracking pattern;
3) qualitative evaluation of geotechnical and hydrogeological instability conditions at the artefact and site scales, respectively.

This note was drafted through the critical interpretation of results, with the objective of providing an overview of the size of the nominated monuments.
The evaluations covered the sites in their entirety, with particular emphasis placed on components considered significant in terms of historical and typological evolution.
Subsequently, the study of the state of preservation of the sites was used to identify categories of actions to be taken in the medium and long term to resolve or minimise ongoing problems. This took into account the work already being done and planned at various sites. Furthermore, risk factors have been identified, and their potential impact on conservation has been determined.

STATE OF CONSERVATION

Interaction between monuments and their natural environment

A multitude of factors must be taken into consideration when assessing the state of conservation of hypogeal monuments. The first aspect that all types of this cultural heritage have in common is their intrinsic connection with the natural environment in which they were constructed. Consequently, they become an integral part of the natural context that hosts them, thereby becoming a single "nature and architecture monument". It can thus be concluded that the landscape constitutes one of the most significant intrinsic values. Consequently, the initial safeguard to be considered is evidently associated with the quality of the environmental and landscape context of reference.
The majority of monumental complexes are to be found in isolated and untouched rural and mountain settings. This condition is advantageous in terms of preserving the identity and authenticity of the monuments, but it introduces factors that can make the maintenance and restoration of the monuments more complex and costly.
Only the site of *Orto del Beneficio Parrocchiale* (6) is fully embedded in an urban context. All other necropolises are located in the outskirts of areas that have been modified by human activity, primarily farmland. The effects of these necropolises on the surrounding landscape are minimal in terms of context.

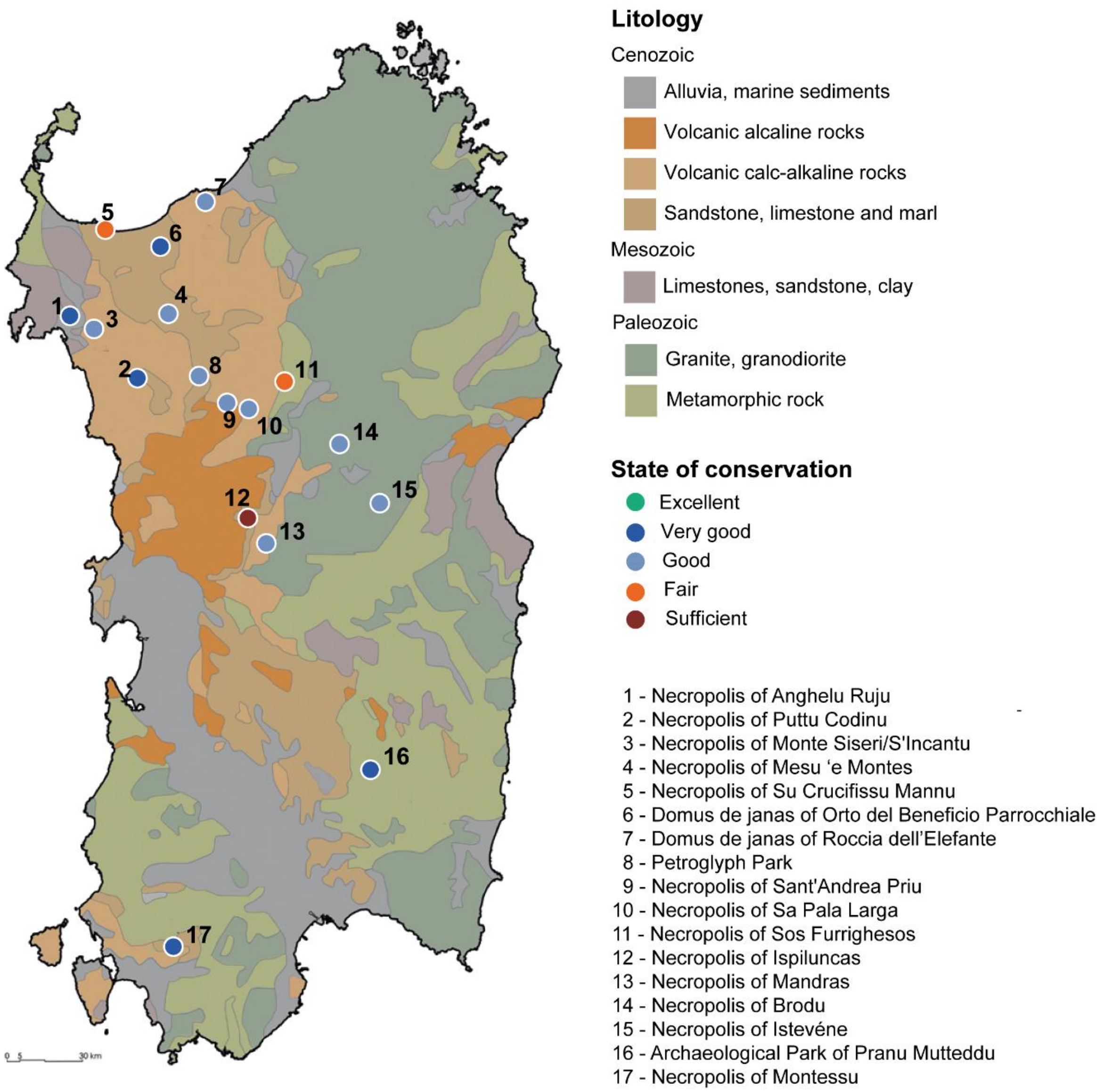

Figure 2. *Distribution of the sites covered by this study on the lithological map of the Sardinia region, and indication of the state of conservation of the archaeological property detected in this study.*

The majority of hypogea have been identified in hilly geomorphological contexts, with a preponderance located on the escarpment of cuestas. It is noteworthy that only three of these necropolises are situated on sedimentary rock substrates in a lowland/pediment geomorphological context on a structural terrace. Exceptions to this include *Roccia dell'Elefante*, which was excavated in an erratic mass, a relic of an ancient collapse prior to the excavation of the necropolis. Another notable exception is Tomb IV of *Istevéne*, which was carved from a single granodiorite monolith.

A secondary intrinsic factor considered is the complexity degree, which is defined as the number of tombs within the area of discovery, as well as the number of chambers in each tomb. Despite the absence of correlations between the complexity of the sites and their state of conservation, it is evident that the number of tombs and the levels of interior arrangement of individual funerary monuments can influence the preservation and maintenance operations, necessitating adequate human and financial resources.

The monuments included in the serial site predominantly exhibit a medium-to-high degree of complexity, encompassing areas with the presence of numerous tombs, frequently distinguished by a range of sizes and levels of preservation. In a similar vein, the tombs that are regarded as being of the greatest interest (i.e. paradigmatic) are predominantly multi-chambered, characterised by a complex interior layout. This is to be considered in relation to the fact that, from a lithotechnical perspective, hypogea has been primarily excavated in soft rocks that are readily manipulable and with favourable mechanical characteristics (e.g., volcanic tuffs, limestones and sandstones).

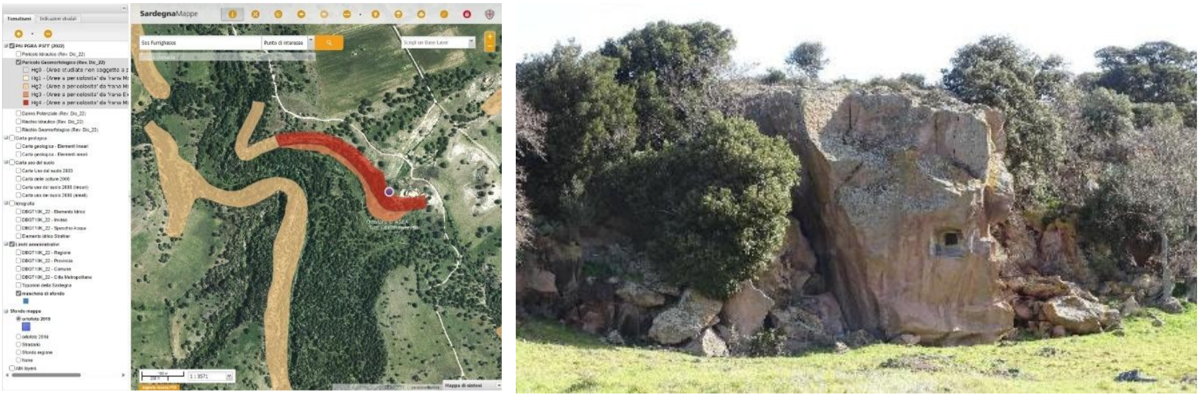

Figure 3. *Landslide hazard map for Necropolis of "Sos Furrighesos", Anela (SS) (left). Rock escarpment, Necropolis of "San'Andrea Priu", Bonorva (SS) (right).*

This facilitated the construction of complex systems comprising multiple rooms and chambers. However, there are several examples of small excavations made of harder rocks, such as igneous intrusive rock and conglomerates.

As shown in Figure 2, the monuments of the serial site are distributed across areas characterised by alkaline and calcalkaline volcanites or sandstones, marls and limestones. The presence of artifacts in areas abundant in granite or metamorphites is comparatively infrequent.

In general, the majority of tombs were excavated in volcanic rocks, predominantly rhyolitic in nature, which exhibit significant variations in the ratio of matrix to phenocrysts, the presence or absence of quartz, and the texture, ranging from moderately welded to welded. Mostly, volcanic tuffs are pyroclastic deposits (ignimbrites) featuring rhyolitic or rhyo-dacitic chemism, locally associated with cinerites in the upper part of the deposit. They appear as rock masses with moderately or poorly fractured structure with a range of main gaps, slightly to poorly degraded, almost parallel to the slope extrados, characterized by high stratum inclination, and wide or very wide spacing.

In less frequent instances, the tombs exhibit a localised fractured or chaotic structure, accompanied by moderately to very degraded gaps. Sedimentary rock masses are distinguished by a structural characteristic that exhibits horizontal or sub-horizontal stratigraphy.

The results of the survey have indicated that geomorphological and lithological factors are the primary contributors to monument state monuments' state of conservation.

At the site scale, these factors appear to predispose the activation of hydrogeological instability mechanisms observed in various necropolises. The types of movement exhibited are consistent with those typically observed in rock clusters characterised by rapid to very rapid kinematics. These include phenomena such as falls, topples, planar landslides and lateral spreads. In the absence of a monitoring system, their activity is considered quiescent.

It is important to note the potential for the impact of hydrogeological instability to be non-uniform across the site, with the possibility of its manifestation being concentrated in specific areas.

The present condition has been documented primarily in larger sites exhibiting greater geomorphological and lithological variability, such as Iloi Ispiluncas (12), Montessu (17), Sant'Andrea Priu (9), and Pranu Mutteddu (16).

In certain cases, it was possible to identify additional factors that triggered the observed phenomena. For instance, erosion at the foot of Riu Buttule was identified for Sos Furrighesos (11), while anthropogenic factors related to quarry operations were identified for Tomb X of Sant'Andrea Priu (9) (Figure 3).

It is imperative that the significance of hydrogeological, meteorological, and anthropogenic factors be meticulously evaluated through the implementation of an appropriate monitoring system and the conduction of more profound analyses of slope stability.

Surface Conservation: lithological and environmental factors

A thorough investigation was conducted into the main pathological alterations affecting the surfaces of the walls and vaults of the cells in each individual tomb. These pathologies have a detrimental effect on the conservation of the monuments, especially the decorations (paintings, bas-reliefs, and engravings). The survey focused specifically on identifying degradation phenomena and their causative agents.

Lithological characteristics

The lithological nature of the monuments affects how architectural surfaces decay and degrade, a process that can easily be traced back to the mineralogical and petrographic characteristics of the fundamental material. Microscopic analysis of the most widespread material at these sites, rhyolite, reveals its inherent textural and structural characteristics, which are defined by good compactness, low porosity and low brittleness. Slow erosion induced by exogenous events increases the material's surface roughness, resulting in moderate bioreceptivity, i.e. the presence of biological deposits and natural or anthropogenic encrustations. Natural degradation (weathering) is therefore rather low and does not significantly affect the preservation of the surfaces. Conversely, weathering is significantly more intense in sites made of limestone, where plant colonisation and surface erosion are generally greater.
Lithology affects the state of conservation of both the site as a whole and its individual architectural surfaces. With regard to surface conservation, it is helpful to categorise them as either undecorated or decorated with relief and painted motifs.
In the former category, the state of conservation is excellent overall, with perfectly visible excavation results.

Environmental factors

The primary aggressive factors pertain to the environment, namely those induced by natural events associated with hydrogeological conditions, the characteristics of the stone, the presence of vegetation, and weathering.
It is imperative that the monumental system finds equilibrium with regard to water. It has been widely observed that a significant proportion of Domus de Janas are constructed in proximity to a watershed or stream, or in any case facing a valley traversed by a river. Consequently, the majority of tombs are affected by high humidity levels due to their proximity to aquifers. However, the most significant source of water in the hypogea is rainwater.
Rainwater seeps in through the hatches as windward water, and as a result of runoff on the surfaces outside the tombs. Furthermore, it has been observed that the phenomenon infiltrates through gaps and fractures, often remaining within the confines of the rooms, thereby inducing periods of significant stagnation.
The issue of removing water from tombs was probably addressed in ancient times through the creation of canals, both inside and outside, to drain water away from the entrance and chambers. Therefore, overall, all the hypogea, including those currently open and those sealed as a result of restoration operations, coexist with water that seeps in as groundwater or rainwater. A delicate environmental balance has been established over time between the artefact and water, which keeps the building in a good state of conservation despite some critical situations. The presence of water mainly results in chromatic changes and water marks. On stone portions affected by earthy surface sediments and exposed to natural light, brown-green biological patinas grow. In most cases, these do not affect the conservation of the material and do not substantially change the spatial and symbolic perception of the monuments.
Different solar irradiance of surfaces due to the variable orientation of the hypogea or preferential water percolation routes has resulted in uneven patina distribution on specific areas of many monuments. In other cases, biological colonisation has affected the entire monument evenly and extensively. Biological patinas are also found, albeit to a lesser extent, inside restricted-access hypogea such as *Sa Pala Larga* (10) and *S'Incantu* (3). A notable exception is Tomb VII of *Sa Pala Larga* (10), where the biological patina is predominantly found on black paint, with thick layers exhibiting a glossy bluish reflection when illuminated at an angle.
The presence of surface sediments is common to all open hypogea, having a variable thickness and grip to the substrate, consisting of accumulations of incoherent materials such as dust, soil, guano.
On the other hand, there are no misuse situations to be reported, other than temporary or permanent visitation by animals. Some hypogea are regularly visited by wild animals such as goats, wild boars, etc., but above all, bat colonies are reported.
Finally, the most widespread change factor is weed vegetation, which varies in magnitude and aggressiveness, ranging from individual herbaceous plants to shrubs and large trees. Generally, it consists of creeping grass or small plants with root systems that are incapable of causing significant damage to surfaces. For this reason, mowing and weeding are regularly performed at most sites by removing the plant's crown without using mechanical equipment that could cause severe damage to structures. However, in some situations, such as Tomb II of *Iloi Ispiluncas* (12), deep cracks caused by the growth of local tree root systems are evident, having infiltrated the rock face where the artefact was

excavated. Nevertheless, in certain circumstances, vegetation can stabilise the natural environment, helping to prevent landslides and collapses.

Erosive processes and material loss

Erosion is a far more alarming issue. In some types of lithotype, erosion leads to decay, increasing the roughness of the surface and facilitating the accumulation of earthy deposits, thereby increasing bio-receptivity. More advanced processes lead to gradual spalling and fracturing.
In tombs excavated in limestone and sandstone, erosion occurs through pulverisation and washout. This can result in substantial losses of stone structures (several centimetres), leading to a reduction in cross-section and a change in the original geometric arrangement. In some cases, such as at *Roccia dell'Elefante* (7), erosion has led to small gaps opening up.
Other results of surface erosion, which are typical of outer walls that are directly exposed to the wind, include alveolisation and pitting. Erosion events also include the anthropogenic act of scraping the surface when entering and leaving rooms in the hypogea. This process is, of course, limited to the threshold of the hatchways and access steps, if available.

Structural stability and safety

In terms of structural safety, the inspections revealed a general absence of significant issues, with only a few exceptions. Due to the unique nature of the hypogea, structural problems are always associated with hydrogeological instability and ongoing surface degradation. The most frequent forms of structural failure at the various sites have been classified according to the following four aspects: i) cracking patterns; ii) masonry instability and collapse mechanisms; iii) gaps and detachment; iv) erosion, decohesion and cross-section reduction

Cracking patterns and instability mechanisms

Cracking patterns found on the excavated surfaces of tombs, architectural elements, and in the immediate proximity of monuments, vary in nature and severity. The degree of severity is defined by depth, amplitude and patterns, depending on the magnitude of the displacements from which they originate. In some cases, the crack is only superficial and can be considered as surface degradation, with no current structural implications except for its integrity, as in the case of *Orto del Beneficio Parrocchiale* (6) and *Brodu* (14). In other cases, the crack is deep and can become a passing crack in some partition elements, as in Tomb I of *Iloi Ispiluncas* (12) (Figure 4). As usual, the distinction between deep or surface cracking was made in relation to the thickness of the affected element.
Cracking patterns, when arranged in specific configurations of through cracks, may result in instability events, commonly referred to as collapse mechanisms, which are connected to the geotechnical issues already mentioned. These events are the most critical and, in general, it is necessary to assess well in advance whether a cracking pattern may evolve into an extreme situation. Collapse mechanisms are rare in hypogeal artefacts and require very specific extreme conditions because they involve significant displacements and rotations, which are generally prevented. No occurrences of such events were recorded during the inspections. However, in the case of tombs excavated on a rocky slope, stability is linked to the condition of the slope, or of portions of it when fractured. Thus, they are related to geological-geotechnical hazard issues. Cases such as *Iloi Ispiluncas* (12), *Mesu 'e Montes* (4) and *Sant'Andrea Priu* (9) are to be referred to this type.
Cracking patterns can overlap and interact with natural gaps in the rock structure, so they must be properly distinguished from them. Past events such as formation events imply the presence of stratigraphic discontinuities, which can be described as natural, and generally stable. In turn, these gaps may interact unfavourably with more recent natural or anthropogenic events. Therefore, it is necessary to analyse not only the current configuration, but also its evolutionary characteristics. For this purpose, surveys must be drafted to map the configuration and local characteristics of the cracking patterns over the medium and long term.

Gaps, detachments and structural weakening

With regard to gaps and detachments, reference is made to the partial or total detachment of more or less deep portions from wall surfaces or elements.
This is generally the natural evolution of major cracks or washouts, and historical cases range from superficial spalling or delamination to the loss of significant portions. Sometimes, detached portions could not be found because they had dissolved, shattered, or been removed.

__Figure 4.__ Observed damage of Tomb I, “Iloi Ispiluncas”, Sedilo (OR):passing crack (left) crack pattern (right).

Alternatively, they may have been found intact at the base of the point of detachment. Detachments are particularly severe when they occur on surfaces, decorations or architectural elements.
If the detachment is the result of a deep crack or traumatic event (e.g. impact or vandalism), critical structural elements may be weakened because they are the point of maximum stress. These elements include pillars, partition walls, entrance shields, hatches, vaults and lintels. In such cases, the damage could worsen. As mentioned above, the causes can be traced back to the exacerbation of events previously discussed in relation to cracking patterns, runoff or erosion. Occasionally, this type of damage is caused by human action, whether intentional or not, such as the vandalism or looting of decorations.
In several examined cases, erosion, decohesion and progressive cross-section reduction have occurred in the exposed surfaces of walls, vaults and various compositional elements affected by rainwater, weathering and biological attack.
This problem, which has been referred to as surface degradation, can produce a significant loss of thickness and volume over time, particularly when the action has been forceful. This can result in the structure becoming critically compromised. Historical cases examined included pillars, partition walls, vaults, parapets and hatches. Runoff caused by stormwater percolating or infiltrating inside monuments is particularly persistent.
In hypogeal artefacts, the inflow of water can be visible and result in frequent flooding. When conditions permit, a significant volume of water can exacerbate mechanical erosion. This is enhanced in the presence of sandstones, less coarse ignimbrites, limestones and calcarenites, where mechanical erosion is combined with chemical dissolution (e.g. of calcium carbonate).
Wind is another factor that has an erosive effect in the long term, especially in combination with rainfall. The erosion of specific surfaces is frequently recorded precisely because of their unfavourable exposure to winds that channel the battering action of rainfall.
In a few cases, freeze-thaw cycles and daily and seasonal temperature gradients were likely to have affected the monument due to its particular exposure. Although their action may accelerate its evolution, it is unlikely that erosion was directly triggered by invasive trees, root systems, mosses and lichens.

EVALUATING OF STATE OF CONSERVATION INDEX

The factors described in the previous sections were analysed on a site-by-site basis, considering both the entire necropolis and the main (or paradigm) tomb of each complex. For each factor, a qualitative synthetic index was defined, expressed as an integer score from 0 (mechanism not detected or negligible) to 4 (highly critical mechanism).
The outcomes of the inspection activities, together with the compilation of all relevant information for each site, made it possible to verify both the effects of recent hydrogeological instability events and the presence of any predisposing factors. This body of evidence was then compared with the hydrogeological hazard previously identified through territorial planning instruments. The results of this assessment are summarised in the indicator W_G, which assumes an integer value from 0 (indicating negligible hydrogeological hazard) to 4 (indicating very high hydrogeological hazard).
The same inspection activities were also carried out inside the burial chambers in order to define the indicators associated with surface degradation and structural damage.

Three categories of surface degradation mechanisms were distinguished, each with its own index: chemical/biochemical ($W_{SD,1}$), physical/mechanical ($W_{SD,2}$), and anthropogenic ($W_{SD,3}$). Similarly, structural safety and crack-pattern indicators were developed to quantify the detected structural damage, including a crack-pattern index ($W_{SS,1}$) and two additional indexes accounting for the presence of gaps ($W_{SS,2}$) and section reduction ($W_{SS,3}$). Combining the indices allows us to define an overall index of the state of conservation (I_C), given by the following relationship:

$$I_c = [1 - (W_G + W_{SD,1} + W_{SD,2} + W_{SD,3} + W_{SS,1} + W_{SS,2} + W_{SS,3}]/(n_L \cdot n_w)*10 \quad (1)$$

where n_L is the number of levels considered for each factor (4 in this case), n_w is the total number of factors considered (7 in this case). The I_c assumes a value between 0 and 10, which is associated with a state of conservation: insufficient (I_c < 6), sufficient (I_c = 6), fair (I_c = 7), good (I_c = 8), very good (I_c = 9), and excellent (I_c = 10).
The results obtained for the 17 necropolises analysed in this study are shown are shown in Figure 2 with a different colour symbol for each site.

CONCLUSIONS

The activities carried out by the interdisciplinary work have provided a comprehensive and methodologically consistent assessment of the state of conservation of the Domus de Janas part of the UNESCO serial property. This assessment formed the basis for Chapter 4 of the nomination dossier for their inscription as a World Heritage Site (UNESCO World Heritage Centre. 2023). Systematic inspection of all identified necropolises — amounting to approximately 300 surveyed tombs — enabled acquisition of a robust, comparable dataset.
A key outcome of this work is the development of a practical, operational indicator I_C that can identify conditions requiring conservation, stabilisation or safety interventions. This indicator synthesises the collected information and provides a decision-support tool for prioritising actions within the broader management plan. In this sense, the study contributes to the definition of evidence-based strategies for the restoration and long-term safeguarding of the monuments, paying particular attention to geological, geotechnical and structural risk conditions.

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