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Protection of Cultural Heritage and Monuments of Nature from the Effects of Climate
Change (CCC)

The Archaeological Site of Delphi under the Threat of Climate Change:
Documentation of Deterioration and Proposals for Conservation and Protection

Master Thesis

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DEDICATION:

Στη μικρή μου αδερφή, που μου υπενθυμίζει πάντα ότι μπορώ.

Στην αγαπημένη μου μητέρα, που πάντα θέλει περισσότερα για εμένα — και ιδιαίτερα σε
εκείνη αφιερώνω αυτή την προσπάθεια.

Σε εκείνον που λείπει, μα είναι πάντα δίπλα μου.

Και στον αγαπημένο μου, που τον ξεποδαριάζω τρέχοντάς τον παντού, αλλά είναι πάντα εκεί,
δίπλα μου, με τον ενθουσιασμό μικρού παιδιού.

Σας ευχαριστώ.

ABSTRACT

This thesis examines the deterioration of stone materials at the Archaeological Site of Delphi, focusing on the Temple of Apollo and the Ancient Stadium. It also examines the natural and environmental factors that may be related to the development and progression of the deterioration observed, as well as the possible influence of changes in climatic parameters. The research is based on a qualitative approach, combining a literature review with macroscopic visual observation and photographic documentation carried out during a field visit on 11 May 2026. The deterioration patterns identified in the two monuments were classified according to the ICOMOS–ISCS terminology and examined in relation to the stone materials and the local exposure conditions of each monument. Cracks, material loss, alveolisation, rounding and biological colonisation were identified in both case studies, while localised displacement and disorganisation of stone elements were also recorded at the Ancient Stadium. The results show that the recorded deterioration cannot be examined in relation to a single environmental factor. Water and moisture, temperature variations, biological activity and vegetation, geodynamic instability, the characteristics of the stone materials and local exposure conditions may contribute in different ways to its development. Although projected climatic changes may modify the future exposure conditions of the monuments, the available evidence does not allow the deterioration recorded during the field investigation to be directly attributed to climate change. Finally, the comparison of the two monuments shows that similar visible deterioration does not necessarily mean that it developed through the same mechanisms, since differences exist in both their stone materials and local exposure conditions. The study therefore supports the need to examine each monument individually and highlights the importance of systematic monitoring for its future conservation and protection.

Keywords: Climate change, cultural heritage, Delphi, stone deterioration, Temple of Apollo, Ancient Stadium, conservation

Περίληψη

Η παρούσα διπλωματική εργασία εξετάζει τη φθορά των λίθινων υλικών στον Αρχαιολογικό Χώρο των Δελφών, με έμφαση στον Ναό του Απόλλωνα και το Αρχαίο Στάδιο. Παράλληλα, εξετάζονται οι φυσικοί και περιβαλλοντικοί παράγοντες που ενδέχεται να σχετίζονται με την ανάπτυξη και την εξέλιξη των φθορών που παρατηρήθηκαν, καθώς και η πιθανή επίδραση των μεταβολών των κλιματικών παραμέτρων. Η έρευνα βασίζεται σε ποιοτική προσέγγιση, συνδυάζοντας βιβλιογραφική ανασκόπηση με μακροσκοπική οπτική παρατήρηση και φωτογραφική τεκμηρίωση που πραγματοποιήθηκαν κατά την επιτόπια επίσκεψη στις 11 Μαΐου 2026. Οι μορφές φθοράς που εντοπίστηκαν στα δύο μνημεία ταξινομήθηκαν σύμφωνα με την ορολογία ICOMOS–ISCS και εξετάστηκαν σε σχέση με τα λίθινα υλικά και τις τοπικές συνθήκες έκθεσης κάθε μνημείου. Και στις δύο περιπτώσεις εντοπίστηκαν ρωγμές, απώλεια υλικού, κυψελοειδής διάβρωση (alveolisation), στρογγυλοποίηση ακμών (rounding) και βιολογική αποίκιση, ενώ στο Αρχαίο Στάδιο καταγράφηκαν επιπλέον τοπικές μετακινήσεις και αποδιοργάνωση λίθινων στοιχείων. Τα αποτελέσματα δείχνουν ότι οι καταγεγραμμένες φθορές δεν μπορούν να εξεταστούν σε σχέση με έναν μόνο περιβαλλοντικό παράγοντα. Η παρουσία και η κίνηση του νερού και της υγρασίας, οι μεταβολές της θερμοκρασίας, η βιολογική δραστηριότητα και η βλάστηση, η γεωδυναμική αστάθεια, τα χαρακτηριστικά των λίθινων υλικών και οι τοπικές συνθήκες έκθεσης μπορούν να συμβάλλουν με διαφορετικό τρόπο στην εξέλιξή τους. Παρόλο που οι προβλεπόμενες κλιματικές μεταβολές ενδέχεται να τροποποιήσουν τις μελλοντικές συνθήκες έκθεσης των μνημείων, τα διαθέσιμα στοιχεία δεν επιτρέπουν την άμεση απόδοση των φθορών που καταγράφηκαν κατά την επιτόπια έρευνα στην κλιματική αλλαγή. Τέλος, η σύγκριση των δύο μνημείων δείχνει ότι η παρουσία παρόμοιων ορατών μορφών φθοράς δεν σημαίνει απαραίτητα ότι αυτές αναπτύχθηκαν μέσω των ίδιων μηχανισμών, καθώς υπάρχουν διαφορές τόσο στα λίθινα υλικά όσο και στις τοπικές συνθήκες έκθεσής τους. Η έρευνα υποστηρίζει επομένως την ανάγκη ξεχωριστής αξιολόγησης κάθε μνημείου και αναδεικνύει τη σημασία της συστηματικής παρακολούθησης για τη μελλοντική προστασία και διατήρησή του.

Λέξεις-κλειδιά: Κλιματική αλλαγή, πολιτιστική κληρονομιά, Δελφοί, φθορά λίθου, Ναός του Απόλλωνα, Αρχαίο Στάδιο, διατήρηση

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1 Introduction

Climate change is one of the most significant challenges of the 21st century, as its impacts affect both natural ecosystems and the built environment (Brimblecombe, 2010). Beyond its environmental consequences, it increasingly affects cultural heritage, which constitutes a fundamental component of historical identity and collective memory (Sesana et al., 2021). Archaeological monuments located in outdoor environments are directly exposed to changes in environmental and climatic conditions, which can influence and accelerate the deterioration mechanisms affecting their materials (Sesana et al., 2021).

The Archaeological Site of Delphi, which is located on the southern slopes of Mount Parnassus in central Greece, constitutes the subject of the present study. The site is distinguished by its exceptional historical and cultural significance, having served as one of the most important religious and spiritual centres of the ancient world (Marinos & Rondoyanni, 2005). The geographical and mountainous location of Delphi strongly influences the climatic conditions of the area. The area is characterised by a continental climate, with warm and dry summers and long, cold winters (Tringa & Tolika, 2023). Rockfalls occur in the area and also affect the archaeological site. This can be associated with the distinctive geomorphology of the area, the steep and heavily fractured limestone slopes, and the presence of geological discontinuities, which favour the occurrence of instability phenomena (Christaras & Vouvalidis, 2010).

1.1 Aim and Research Questions

The aim of this thesis is to identify, document and analyse the deterioration phenomena observed at the Archaeological Site of Delphi, focusing more specifically on the Temple of Apollo and the Ancient Stadium. The deterioration phenomena identified are recognised and classified according to the ICOMOS–ISCS terminology, while the natural and environmental factors that may contribute to their development and progression are also examined. The thesis further examines the potential influence of changes in climatic parameters and compares the two monuments in terms of their deterioration phenomena and the factors that may affect them.

Based on this objective, the main research questions of the present study are formulated as follows:

1. What are the main deterioration phenomena observed in the stone monuments of the Archaeological Site of Delphi?
2. Which natural and environmental factors may contribute to the development of these deterioration phenomena?
3. How may changes in climatic parameters be associated with the development and progression of the observed deterioration phenomena?
4. What similarities and differences can be identified between the two case studies, the Temple of Apollo and the Ancient Stadium, in relation to the observed deterioration patterns, construction materials, and their exposure conditions?

1.2 Methodological Approach

The methodological approach selected for conducting this research is based on a qualitative research framework and relies primarily on a literature review. The literature research focused on scientific and institutional sources concerning climate change and cultural heritage, the deterioration of stone materials, climatic and environmental deterioration mechanisms and, more specifically, the impacts of climate change in the Mediterranean region and Greece, as well as the geological, environmental and archaeological context of Delphi. The selection of sources was based on their relevance to the research questions addressed in this study, as well as their scientific or institutional reliability. The literature includes scientific articles, academic publications and books, as well as reports and guidelines from recognised international organisations, such as the IPCC, UNESCO and ICOMOS. No strict publication date restriction was applied, as earlier sources were also included when considered relevant to the theoretical framework or the specific subject of the study.

The fieldwork was conducted on 11 May 2026 and consisted of a single visit to the Archaeological Site of Delphi, focusing more specifically on the Temple of Apollo and the Ancient Stadium. The area of observation was limited exclusively to areas accessible to visitors, as no special access permission was available. During the visit, visual observation and photographic documentation of the two monuments were carried out, without measurements or sampling. The photographic documentation focused on recording visible forms of deterioration, while additional deterioration phenomena observed during the field visit were also recorded. All photographs used for the field documentation in this study were taken by the author during this visit.

Following the completion of the fieldwork and the evaluation of the photographic material, the deterioration phenomena observed at the two monuments were identified and classified. The classification of the deterioration phenomena was based on the ICOMOS–ISCS (2008) terminology, so that the different forms of deterioration could be described using common and recognised criteria. The deterioration phenomena identified were then examined in combination with the relevant literature and the natural and environmental conditions of the area in order to investigate the factors that may contribute to their development and progression. This approach cannot establish a direct causal relationship between an environmental or climatic factor and a specific form of deterioration, but it allows possible associations to be investigated based on the observations and the available literature.

Regarding the comparative assessment of the Temple of Apollo and the Ancient Stadium, common criteria were applied to both monuments. These criteria include the deterioration phenomena observed and classified, the characteristics of the construction materials, the different exposure conditions of the two monuments, and the natural and environmental factors that may be associated with the observed deterioration. The aim of the comparison is to identify the main similarities and differences between the two monuments and to examine whether their different conditions and characteristics may be associated with the different forms of deterioration observed.

The limitations of the present research are initially related to the fact that the observation and photographic documentation were based on a single visit and were limited to the areas of the monuments accessible to visitors. In addition, no measurements, sampling or laboratory analyses were carried out and, therefore, the assessment is based on visual observation, photographic documentation and the relevant literature. At the same time, contact was made with the competent Ephorate of Antiquities with the aim of collecting data and additional information regarding previous conservation interventions and the existing state of conservation of the monuments. Through this communication, it was not possible to obtain material relevant to the subject of the research and, consequently, no data or information from the Ephorate of Antiquities were used in the present study.

1.3 Structure of the thesis

This thesis is organised into several chapters. The first chapters present the theoretical framework concerning climate change and its impacts on cultural heritage, as well as the main deterioration mechanisms affecting stone materials, followed by the natural and environmental characteristics of the Archaeological Site of Delphi. The subsequent chapter investigates the deterioration phenomena observed in the selected monuments, with particular emphasis on the Temple of Apollo and the Ancient Stadium. This is followed by a Discussion and Comparative Assessment of the two monuments, where the findings are examined in relation to the research questions. Finally, the thesis presents the main conclusions of the research and proposes measures for the conservation and protection of the monuments.

2 Climate Change and Cultural Heritage

2.1 Climate Change and its Environmental Impacts

Climate change affects both natural ecosystems and human systems on a global scale and is associated with significant changes in the Earth's climate system. According to the Intergovernmental Panel on Climate Change (IPCC), human activities have caused extensive and, in many cases, unprecedented changes to the Earth's climate system over timescales ranging from centuries to millennia (IPCC, 2021). The increasing concentration of greenhouse gases in the atmosphere, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), has intensified the greenhouse effect and consequently contributed to an increase in global mean temperature of approximately 1.1°C above pre-industrial levels during 2011–2020 (IPCC, 2021).

The most visible and widely perceived manifestation of climate change is the increase in temperature. However, the phenomenon is not limited to warming alone. The climate system is undergoing broader transformations, including changes in precipitation patterns, an increase in the frequency and intensity of extreme weather events, and significant alterations in the oceans. These changes include rising sea temperatures, ocean acidification caused by the absorption of carbon dioxide, and declining levels of dissolved oxygen, all of which directly affect the functioning of marine ecosystems (IPCC, 2021).

An important characteristic of climate change is the increasing variability of the climate system. Extreme weather events, such as heatwaves, intense precipitation, and droughts, are occurring with greater frequency, intensity, and duration, indicating a broader destabilisation of climatic conditions (IPCC, 2022). Recent literature also highlights the significance of compound events, namely the simultaneous or successive occurrence of multiple climatic stressors, such as high temperatures, droughts, and heavy rainfall. The combined action of these factors does not merely produce cumulative impacts but may generate multiplicative effects, significantly increasing overall environmental stress (Zscheischler et al., 2020).

Changes in the hydrological cycle are also of major importance and are closely associated with rising temperatures. Enhanced evaporation leads to increased atmospheric moisture content, resulting in more intense precipitation events as well as prolonged drought periods. This

alternation between wet and dry conditions creates severe environmental stress, affecting both natural ecosystems and materials exposed to outdoor environments (Brimblecombe, 2010; Camuffo, 2019).

Sea-level rise represents another significant consequence of climate change. This phenomenon is primarily associated with two mechanisms: the thermal expansion of seawater resulting from increasing ocean temperatures and the melting of glaciers and polar ice sheets. The combined action of these processes leads to a gradual yet accelerating rise in sea level, increasing coastal risk through shoreline erosion, flooding events, saltwater intrusion into groundwater resources, and land loss (Cazenave & Nicholls, 2010; IPCC, 2021). These impacts are not uniform but depend on local factors, including coastal geomorphology, land subsidence, human activities, and the level of protective infrastructure.

2.2 Climate Change in the Mediterranean Region

The Mediterranean region is considered particularly vulnerable to climate change and is widely recognised as a climate-change hotspot. Its vulnerability stems not only from rising temperatures but also from the coexistence of multiple interacting climatic hazards. The literature documents an increase in the frequency, duration, and intensity of heatwaves, a decline in summer precipitation, and a growing frequency and severity of droughts (IPCC, 2021; IPCC, 2022). At the same time, increasing temperatures combined with reduced soil and vegetation moisture create favourable conditions for the occurrence and spread of wildfires, which form part of a broader framework of mutually reinforcing climatic pressures (Cramer et al., 2018; Turco et al., 2018). The interaction of these phenomena creates a complex risk system that significantly increases the overall vulnerability of the region.

A key concept in understanding the impacts of climate change in the Mediterranean region is compound vulnerability, which arises from the interaction between natural processes and socio-economic factors. In the Mediterranean, high population concentrations in coastal areas, intensive tourism activity, the dependence of agriculture on limited water resources, and the remarkable concentration of cultural heritage assets increase both the exposure and sensitivity of natural and human systems (Cramer et al., 2018; IPCC, 2022). As a result, even moderate changes in climatic conditions may produce disproportionately large impacts on ecosystems, human activities, and cultural heritage sites.

Future projections further reinforce the classification of the Mediterranean as a region of high climate risk. Under high-emission scenarios, further increases in temperature, significant reductions in water availability, and intensified desertification processes are expected, particularly in the southern and eastern parts of the Mediterranean Basin (IPCC, 2021; IPCC, 2022; Cramer et al., 2018). These projections make the Mediterranean one of the most critical regions for understanding the interactions between climate change, natural systems, human activities, and cultural heritage.

2.3 Climate Change in Greece

Within this context, Greece, as part of the Mediterranean region, is among the areas expected to be significantly affected by the impacts of climate change. Studies have identified significant changes in the climatic conditions of the country, both in terms of temperature and precipitation and in the occurrence of extreme weather events (Giannakopoulos et al., 2009). These changes create conditions of increased environmental stress, particularly in areas characterised by complex geomorphology, such as mountainous landscapes and archaeological sites.

According to climate model projections for Greece, a significant increase in mean temperature is expected throughout the twenty-first century, with the most pronounced changes occurring during the summer months, particularly in the southern and mainland regions of the country (Giannakopoulos et al., 2009). This increase is associated with more frequent, intense, and prolonged heatwaves, which represent one of the most characteristic manifestations of contemporary climate change in Greece. At the same time, a substantial decline in precipitation is projected, especially during the summer season, leading to increasing water stress and intensified drought conditions.

The reduction in water availability represents one of the most significant consequences of climate change for Greece. Prolonged drought periods, combined with high temperatures and increased evaporation rates, affect both natural ecosystems and human activities, including agriculture, water management, and tourism (Giannakopoulos et al., 2009). Furthermore, changes in the hydrological cycle are accompanied by an increase in the intensity of extreme rainfall events, which may trigger flooding, soil erosion, and slope instability, particularly in areas characterised by steep and complex terrain (IPCC, 2022).

Contemporary literature indicates that climate change in Greece is not manifested through isolated phenomena but rather through the interaction of multiple climatic pressures. Recent studies on compound climate extremes highlight that the simultaneous occurrence of high temperatures and prolonged drought is becoming increasingly frequent across the country, creating conditions of particularly intense environmental stress. The combined effects of heat and aridity increase the likelihood of large-scale wildfires while also enhancing the susceptibility of soils and materials to erosion and weathering processes (Mathbout et al., 2025).

The increasing wildfire risk constitutes one of the most significant dimensions of climate change in Greece. High temperatures, low humidity levels, and prolonged dry periods create favourable conditions for the occurrence and spread of high-intensity wildfires, which affect not only natural ecosystems but also archaeological sites and historic landscapes (Cramer et al., 2018). Furthermore, following wildfire events, the risk of flooding and erosion processes increases considerably due to vegetation loss and changes in surface runoff patterns.

Sea-level rise also represents an important aspect of climate change impacts in Greece. According to Cazenave and Nicholls (2010), this phenomenon is primarily associated with the thermal expansion of the oceans and the melting of glaciers and polar ice sheets. For a country characterised by an extensive coastline and a large number of coastal and island regions, these impacts are of particular significance, as they are associated with an increased risk of coastal erosion, flooding events, and saltwater intrusion into coastal aquifers.

2.4 Climate change and Cultural Heritage Vulnerability

The relationship between climate change and cultural heritage is of particular importance, as environmental changes may affect both materials and structures. The approach proposed by Brimblecombe (2010) is especially significant, as it emphasises that climate change does not necessarily generate new deterioration mechanisms but rather accelerates and intensifies existing processes. Mechanisms such as thermal expansion and contraction, wetting–drying cycles, salt dissolution and crystallisation, and weathering processes are already well known; however, changes in climatic parameters influence their frequency, intensity, and duration (Brimblecombe, 2010).

The importance of local environmental conditions is further highlighted by Camuffo (2019), who distinguishes between macroclimate and microclimate. General climatic indicators, such as mean temperature or total precipitation, do not affect materials in a simple or direct manner. Instead, the impacts of climate change are expressed through local microclimatic conditions, which are determined by factors such as the orientation of a monument, exposure to solar radiation, air circulation, the presence of moisture, and site topography (Camuffo, 2019). Within this framework, material deterioration is more closely associated with fluctuations in environmental parameters than with their average values. Repeated heating–cooling and wetting–drying cycles generate mechanical and physicochemical stresses that may lead to cracking, exfoliation, weathering, and material loss.

Similarly, the study by Sesana et al. (2021) contributes to the theoretical understanding of cultural heritage vulnerability by proposing a multifactorial approach. According to this perspective, the vulnerability of monuments is not a static property but results from the dynamic interaction between climatic pressures, material properties, and site characteristics. Factors such as porosity, mineralogical composition, and the mechanical strength of materials determine how they respond to environmental stresses, while geographical location, elevation, orientation, and topography influence the degree of exposure of a monument to climatic hazards (Sesana et al., 2021).

Recent literature also highlights that research on climate change and cultural heritage has primarily focused on documenting and analysing deterioration phenomena, while the adaptation dimension remains less developed. Orr et al. (2021) point out that, although significant progress has been made in understanding climate-related risks and deterioration mechanisms, the transition from problem diagnosis to the development of practical protection strategies has not yet been fully achieved. This research gap underscores the need for studies that link the documentation of deterioration phenomena with risk assessment and the development of management and adaptation strategies.

In conclusion, understanding the interaction between climatic and environmental factors and cultural heritage is essential for interpreting deterioration processes and provides an important basis for the development of effective conservation and protection strategies.

2.5 Environmental and Climatic Mechanisms of Stone Deterioration

Stone materials are strongly influenced by local environmental conditions, as fluctuations in temperature and moisture may affect their physical and physicochemical behaviour (Camuffo, 2019).

Environmental factors directly influence the behaviour of building materials and can be grouped into three main categories: parameters related to temperature, parameters associated with water and moisture, and parameters linked to wind, particle transport, and salts (Brimblecombe, 2010).

2.5.1 Temperature and Moisture Fluctuations

Intense environmental fluctuations associated with climate change are considered particularly critical for the preservation of monuments. Repeated heating–cooling and wetting–drying cycles generate continuous mechanical and physicochemical stresses within materials (Camuffo, 2019). Thermal expansion and contraction create internal stresses and microcracks, gradually weakening the structural integrity of stone materials, while variations in moisture influence the movement of water and dissolved salts within the pore network of the material.

Temperature also plays a major role in material deterioration, as it affects both the physical and chemical processes occurring within materials. As temperature increases, chemical reactions accelerate, evaporation intensifies, and thermal stress becomes more pronounced. At the same time, temperature fluctuations contribute to repeated cycles of expansion and contraction, leading to crack formation and the gradual deterioration of the stone microstructure (Camuffo, 2019).

2.5.2 Wetting – Drying and Salt Crystallisation

Wetting and drying cycles constitute an important deterioration mechanism affecting porous stone materials. When water enters the pores of a stone and subsequently evaporates, dissolved salts, if present within the material, may crystallise generating internal pressures that may lead to weathering, exfoliation, and detachment of surface layers (Camuffo, 2019). This process depends not only on the presence of water but, more importantly, on the frequency and intensity of environmental fluctuations, as repeated wetting and drying cycles significantly accelerate deterioration processes.

2.5.3 Capillary Rise and Condensation

Another important factor associated with the presence of water and material deterioration is capillary rise, which depends not only on the direct exposure of a monument to water but also on the way in which a material absorbs, retains, and releases moisture. Capillary rise refers to the movement of water from lower to higher levels through the pore network of materials. This process allows moisture to penetrate and migrate within stone even when it does not originate directly from rainfall (Camuffo, 2019).

Equally important is the phenomenon of condensation. When temperature and humidity conditions are favourable, water vapour may condense on cool surfaces or within micropores, allowing the presence of liquid water even in the absence of precipitation. Consequently, a monument may undergo deterioration not only when it is directly exposed to rainwater but also when the surrounding microclimate promotes condensation and moisture retention.

2.5.4 Biological Growth

The presence of moisture and water also contributes to biological growth. Elevated moisture levels and high relative humidity create favourable conditions for the development of organisms such as lichens, algae, and microorganisms. The deterioration caused by these organisms is not merely superficial but can be substantial, as they contribute to both the chemical and mechanical degradation of materials (Camuffo, 2019).

2.5.5 Critical Environmental Thresholds and Freeze – Thaw Cycles

It is especially important to note that even relatively small changes in environmental parameters may result in disproportionately large impacts on materials. Once environmental conditions exceed certain critical thresholds, specific deterioration mechanisms are activated. Many processes associated with stone weathering depend on particular temperature and humidity conditions. Consequently, even a relatively minor environmental disturbance may be sufficient to shift a material from a stable condition to one of active deterioration (Brimblecombe, 2010).

Similarly, in freeze–thaw cycles, temperature acts as a critical threshold. When temperatures fall below the freezing point, water contained within the pores of stone materials freezes and expands in volume. This volumetric expansion generates mechanical stresses within the material. The continuous repetition of the freezing and thawing process of water within the

pore network may cause an increase in mechanical stresses, which can lead to crack formation and increased vulnerability of the stone structure (Brimblecombe, 2010).

2.6 ICOMOS – ISCS and the Classification of Stone Deterioration Patterns

The systematic documentation and classification of deterioration phenomena constitute a fundamental step in understanding the pathology of monuments and in selecting appropriate conservation and protection measures. In this context, particular importance is attributed to the ICOMOS–ISCS *Illustrated Glossary on Stone Deterioration Patterns*, which represents one of the most widely recognised international tools for the identification and description of deterioration forms affecting stone heritage (ICOMOS–ISCS, 2008).

The International Council on Monuments and Sites (ICOMOS) International Scientific Committee for Stone (ISCS) was established with the objective of developing a common scientific terminology related to stone deterioration, thereby facilitating communication among conservators, engineers, geologists, and cultural heritage researchers (ICOMOS–ISCS, 2008). The existence of a shared terminology is considered essential in order to ensure that deterioration phenomena can be systematically identified, compared, and evaluated across different monuments and geographical contexts.

According to the glossary, deterioration patterns are classified into six principal families: general terms of deterioration, cracks and deformations, detachments, material loss features, discoloration and deposits, and biological colonisation (ICOMOS–ISCS, 2008). This classification is based primarily on the macroscopic observation of deterioration patterns, placing emphasis on their morphology rather than exclusively on the mechanisms responsible for their formation (ICOMOS–ISCS, 2008).

In the present study, the ICOMOS–ISCS glossary is used for the identification and classification of the deterioration patterns observed in the areas under study. The documentation is based on macroscopic visual observation and photographs taken during the field visit. The deterioration patterns identified are examined in relation to the environmental conditions of the area. However, the exact causes of these specific deterioration patterns cannot be determined through visual observation alone.

3 Case Study: Delphi

3.1 Historical Development of Delphi

The archaeological site of Delphi is one of the most important centers of ancient Greek religion and an iconic monument of global cultural heritage. The enduring significance of the sanctuary is associated with both its religious and political value, as numerous city-states sought to connect their presence and prestige with the sanctuary of Delphi, extending their influence across both the eastern and western parts of the Greek world. At the same time, the sanctuary is inextricably linked to the natural landscape of Mount Parnassus and the geomorphology of the surrounding area. For the ancient Greeks, Delphi was considered the “center of the world,” and its history is closely associated with mythology, the worship of Apollo, and the operation of the Oracle (UNESCO, n.d.).

This sacred site functioned as a point of communication between humanity and the divine, expressing the timeless human desire to seek answers about the future and interpret the will of the gods. For this reason, the Oracle’s prophecies were regarded as highly significant and influenced political, military, and social decisions. The sanctuary was primarily associated with the worship of Apollo; however, other cult practices were also present, including the worship of Dionysus, which appears to have been connected with specific periods of the year and particular ritual activities (Hellenic Ministry of Culture, n.d.).

According to ancient tradition, Zeus released two eagles from opposite ends of the earth, and they met at Delphi. This event led to the placement of the stone Omphalos, symbolizing the center of the inhabited world (UNESCO, n.d.). Prior to the predominance of Apollo’s cult, the area appears to have been associated with earlier chthonic cults, particularly the worship of Gaia and Python, the mythical serpent who, according to Greek mythology, was slain by Apollo, who subsequently established his oracle at the site (Hellenic Ministry of Culture, n.d.)

The sanctuary can be traced back to the Geometric and Archaic periods; however, it reached its greatest prosperity primarily between the sixth and fourth centuries BCE. During this period, the Oracle acquired a Panhellenic character and evolved into an important religious and political center. Cities, kings, and rulers from different regions of the Greek world visited

Delphi to consult the Oracle, dedicate offerings, and enhance their prestige through their association with the sanctuary (Hellenic Ministry of Culture, n.d.).

The Pythia, Apollo's priestess, was directly connected to the operation of the Oracle, serving as a medium of communication between the god and humanity by conveying Apollo's prophecies. These prophecies influenced important political and military decisions, colonial enterprises, alliances, and military campaigns, making Delphi a point of reference for the entire Greek world. The influence of the sanctuary extended far beyond the sphere of religious worship, as Delphi also functioned as a center of political and cultural interaction among the Greek city-states (Hellenic Ministry of Culture, n.d.).

A decisive role in the administration and protection of the sanctuary was played by the Delphic Amphictyony, a religious association of Greek tribes and city-states responsible for supervising and managing the sanctuary. Through the Amphictyony, the Panhellenic character of Delphi was further strengthened, and the sanctuary evolved into a symbol of unity and shared cultural identity throughout the Greek world (Hellenic Ministry of Culture, n.d.).

The Pythian Games, held in honor of Apollo, were one of the four major Panhellenic festivals of antiquity. These games included athletic, musical, and poetic competitions and contributed significantly to the cultural prestige of the sanctuary. Their organization led to the construction of important monumental structures, such as the Ancient Stadium and the Theatre, which were harmoniously integrated into the natural landscape of the sanctuary. During the Hellenistic and Roman periods, Delphi retained its significance, although it gradually began to show signs of decline. The spread of Christianity and the prohibition of ancient religious practices during the Late Roman period ultimately led to the cessation of the Oracle's activities. Subsequently, the site was gradually abandoned, and many of its ancient structures became buried beneath accumulated deposits and later settlements (Hellenic Ministry of Culture, n.d.).

In the nineteenth century, the excavations conducted by the French School at Athens brought the archaeological site of Delphi back to light. Since then, Delphi has remained one of the most important archaeological sites in Greece and a major focus of international scholarly research (Hellenic Ministry of Culture, n.d.).

The significance of Delphi was further recognized at the international level in 1987, when the archaeological site was inscribed on the UNESCO World Heritage List due to its exceptional historical, cultural, and symbolic value (UNESCO, n.d.). UNESCO recognizes Delphi not only as an important archaeological site but also as a distinctive cultural landscape in which human activity is closely intertwined with the natural environment of Mount Parnassus. This unique relationship between cultural heritage and the surrounding landscape contributes significantly to the site's Outstanding Universal Value and reinforces its status as one of the most important cultural heritage sites in the world. (UNESCO, n.d.).

3.2 Temple of Apollo at Delphi

3.2.1 Historical Development and Significance of the Monument

The Temple of Apollo constitutes the most important monument within the archaeological site of Delphi and the central focal point of the sanctuary. Its significance is inseparably linked to that of the Delphic Oracle, which in antiquity was one of the most important religious and political centers of the Greek world. Within the temple was located the adyton, the most sacred area of the Oracle, where the Pythia delivered Apollo's prophecies to cities, rulers, and individuals who traveled from across the Greek world seeking divine guidance for important political, military, or personal decisions (Scott, 2014; Hellenic Ministry of Culture, n.d.).

The earliest evidence of organized worship in the area dates back to the Geometric period, while the gradual development of the Oracle led to the construction of successive temples dedicated to Apollo. Earlier cult structures preceded the historical temple, demonstrating the long-standing religious significance of the site. During the Archaic period, Delphi evolved into a Panhellenic religious center, a development accompanied by extensive building activity and the construction of monumental structures that enhanced the prestige and influence of the sanctuary (Scott, 2014).

A significant milestone in the history of the monument was the fire of 548 BCE, which destroyed the existing temple. In its place, the renowned Temple of the Alcmaeonidae was erected, a project financed by the prominent Athenian family of the same name and considered one of the most important architectural achievements of the Archaic period. Its period of use

coincided with the era during which the Oracle was at the height of its political, religious, and symbolic influence throughout the Greek world (Scott, 2014).

The history of the monument was profoundly influenced by the natural processes that characterize the Delphic landscape. Around 373 BCE, the temple suffered severe damage following a major seismic event and associated rockfall. This destruction forms part of the broader geodynamic framework of the region, discussed in previous chapters, and is closely related to the active tectonic processes of the Corinth Rift system. The need to restore the most important monument of the sanctuary led to an extensive reconstruction program organized under the supervision of the Delphic Amphictyony and financed through contributions from cities and rulers throughout the Greek world (Vanden Broeck-Parant, 2021).

The temple that survives and remains visible today belongs to this fourth-century BCE construction phase and represents the result of the sanctuary's reconstruction following the destruction. Its enduring presence at the center of the archaeological site reflects the continuing importance of the Oracle in the ancient world, while simultaneously illustrating the long-term interaction between humans, the natural environment, and cultural heritage that characterizes the case of Delphi. Despite its enduring significance, the temple remained continuously exposed to the natural processes that shape the Delphic landscape, a factor that influenced both its historical development and its present state of preservation. For this reason, the study of its architectural characteristics, construction materials, and deterioration mechanisms constitutes a fundamental prerequisite for understanding its vulnerability to contemporary environmental and climatic pressures.

3.2.2 Architectural Characteristics and Construction Materials of the Temple of Apollo

The temple that survives today at Delphi belongs to the fourth-century BCE construction phase and represents one of the most significant examples of Late Classical Doric architecture. It is a peripteral Doric temple, built on the central terrace of the sanctuary and occupying a dominant position within the archaeological site. Its location approximately midway along the Sacred Way emphasized its primary role in the operation of the Oracle and the overall organization of the sanctuary, as the majority of votive offerings, treasures, and ceremonial routes were arranged around it (Hellenic Ministry of Culture, n.d.).

Within the temple was the adyton, the most important sacred space of the Oracle, where the Pythia delivered the prophecies of Apollo. The presence of the adyton endowed the temple with a distinctive character, as it functioned not merely as an architectural monument but as the core of the prophetic process and the religious life of Delphi. Its architectural configuration served both ritual and symbolic purposes, reflecting the central role of the Oracle in the ancient Greek world (Scott, 2014).

Beyond its religious and architectural significance, the construction materials used in the temple are of particular interest, as they are directly related to the monument's long-term preservation. According to de Vals et al. (2020), the majority of the monuments within the sanctuary were constructed using stone materials derived from the immediate geological environment of Delphi.



Figure 1. Lithological map of the Sanctuary of Apollo at Delphi, showing the spatial distribution of the principal stone materials used in the monuments of the archaeological site, including Prophet

Elias limestone, Parnassus limestone, rudist limestone, and slope breccia formations (modified from de Vals et al., 2020).

The distribution of the different lithological types within the monuments of the Sanctuary of Apollo is illustrated in the lithological map published by de Vals et al. (2020). The map demonstrates that the ancient builders primarily utilized locally available stone materials, including Prophet Elias limestone, Parnassus limestone, rudist limestone, and slope breccia, while imported stones were employed in certain monuments.

During the reconstruction of the Temple of Apollo in the 4th century BC, Profitis Ilias limestone was extensively used, extracted from quarries located approximately 5 km west of Delphi. However, the monument has a complex lithological composition and is not composed exclusively of this particular material. Profitis Ilias limestone is found in the floor, while slope breccia, marble, and oolitic grainstone have been identified in the foundations, and oolitic grainstone in the columns (de Vals et al., 2020).

The reason why the Temple should be examined as a whole is that the presence of different lithological types is essential when assessing its state of conservation, given that each construction material may exhibit different behaviour when exposed to environmental conditions.

3.3 Ancient Stadium of Delphi.

3.3.1 Historical Development and Architectural Characteristics of the Ancient Stadium of Delphi.

The Ancient Stadium of Delphi is situated at the northwestern edge of the archaeological site, on the highest terrace of the Sanctuary of Apollo, above the ancient theatre and between the Phaedriades Cliffs and the hill of Profitis Ilias (Hellenic Ministry of Culture, n.d.). Its location within the sanctuary reflects the close relationship between athletic competitions, the religious function of the Delphic Oracle, and the worship of Apollo (Scott, 2014).

The construction of the stadium dates to the second half of the fourth century BCE or the beginning of the third century BCE and is associated with the celebration of the Pythian Games, one of the most important Panhellenic festivals of antiquity (Hellenic Ministry of Culture, n.d.). The venue was primarily used for track and field events, which formed part of the ceremonial

program held in honor of the god Apollo (Scott, 2014). Throughout its long period of use, the monument underwent successive construction phases and modifications, which ultimately shaped its present form (Hellenic Ministry of Culture, n.d.).

The stadium is considered one of the best-preserved ancient stadiums in Greece (Hellenic Ministry of Culture, n.d.). The track originally measured approximately 178 m in length, although certain modifications were introduced during the Roman period. The seating tiers extend along both sides of the track and terminate at the western semicircular end, known as the sphendone. The northern side takes advantage of the natural slope of the terrain, whereas the southern side is supported by a retaining wall, demonstrating the adaptation of the monument to the distinctive topography of Delphi (Hellenic Ministry of Culture, n.d.).

According to Pausanias, Herodes Atticus financed major improvements to the stadium during the Roman period, highlighting the enduring importance of the monument even during the imperial era (Hellenic Ministry of Culture, n.d.). The stadium underwent a final major phase of modification during the Roman period, including interventions to the spectator seating. On the eastern side, the starting line of the foot races is preserved, featuring characteristic grooves indicating the positions of the athletes as well as sockets associated with the starting mechanism (Hellenic Ministry of Culture, n.d.).

The principal construction materials of the monument consist of local limestone and carved natural bedrock (Hellenic Ministry of Culture, n.d.). The way in which these materials are exposed to the environmental conditions of the area, in relation to the geomorphology and the local exposure conditions of the monument, represents an important parameter for examining their state of conservation. The possible relationship between the characteristics of the materials, the exposure conditions, and the observed deterioration patterns is examined in the following sections.

3.3.2 Construction Materials of the Ancient Stadium.

The location and historical significance of the Ancient Stadium indicate that it is one of the most important monuments within the archaeological site of Delphi. It is particularly noteworthy that the structure is fully integrated into the natural topography of Mount Parnassus and makes extensive use of locally available geological materials.

According to de Vals et al. (2020), the principal construction material of the Stadium is Parnassus limestone, which was quarried from local extraction sites situated in close proximity to the monument. In addition, slope breccia was employed, a geological material naturally occurring in the region and extensively utilized in the construction of the sanctuary.

The selection of local stone materials was related both to their availability and to practical considerations concerning transportation. The availability of stone materials within and around the archaeological site offered practical advantages for their extraction and transportation, while the so-called Stadium Quarry, located immediately above the Stadium, appears to have been used for the construction of the monument.



Figure 2. The Stadium Quarry, located above the Ancient Stadium of Delphi which is considered one of the probable sources of the Parnassus limestone used in the construction of the monument (adapted from de Vals et al., 2020).

3.4 Natural and Environmental Setting of Delphi

The historical and religious significance of Delphi cannot be examined independently of the unique natural environment within which the sanctuary developed. The location of the archaeological site is particularly significant, as it is situated on the southern slopes of Mount Parnassus, within a mountainous and geomorphologically active landscape, between the steep rocky masses of the Phaedriades Cliffs and above the Pleistos Valley. Morphologically, the area is characterized by steep slopes, rocky formations, rugged topography, and significant

geological discontinuities, all of which played a decisive role in shaping both the natural landscape and the development of the sanctuary itself.

The close relationship between Delphi and its surrounding natural environment appears to have endowed the site with a distinctive physical and symbolic dimension from antiquity. The Delphic landscape was not merely the geographical setting for the development of the monumental complex but constituted an active element of the religious practices and identity of the sanctuary. The various components of the natural environment contributed to the creation of a place of profound spiritual and symbolic significance and became closely associated with the operation of the Oracle and the worship of Apollo.

Geotectonically, the Delphi region forms part of the broader Corinth Rift system, one of the most tectonically active regions in Greece and, more generally, in the Eastern Mediterranean. According to Piccardi (2000), the Corinth fault system forms an asymmetric tectonic graben with a general east–west orientation, characterized by high deformation rates and intense seismic activity. The active extension affecting the region is expressed through continuous tectonic processes, surface faulting, and strong seismic events, which have continuously shaped the geomorphological relief of the area.

Particular importance is attributed to the Delphi Fault, which bounds the southern flank of Mount Parnassus and constitutes one of the most significant active antithetic structures within the Corinth Rift system. The fault is described as a normal fault with an east–west orientation and a southward dip, while also exhibiting a minor dextral strike-slip component. The geological and geomorphological evidence presented by Piccardi (2000) indicates that the fault remains active today, as demonstrated by contemporary seismicity and the occurrence of recent fault ruptures even within Holocene deposits.

The geology of the region is dominated by Mesozoic limestone formations, flysch deposits, and Quaternary sediments, while the presence of extensive scree accumulations and slope deposits reflects the continuous action of weathering processes and gravitational mass movements. The natural environment of the area is characterized by significant geodynamic instability due to its intense tectonic activity and rugged geomorphology. Consequently, rockfalls, landslides, and seismically induced ground movements have been recurring natural phenomena throughout the region's history (Piccardi, 2000; Valkaniotis et al., 2011).

The contribution of Piccardi (2000) is particularly important because he does not examine the Delphi Fault solely as a geological feature but attempts to establish a connection between active geodynamic processes and the very origin and operation of the Oracle. According to his study, the presence of an active fault directly beneath the earliest sanctuary may be related to the tradition of the “prophetic chasm,” namely the opening in the ground from which, according to ancient sources, vapors emerged and induced the ecstatic state of the Pythia.

In the case of Delphi, this hypothesis is especially intriguing because it directly links the natural environment with religious experience and the development of the site’s mythology. Ancient traditions describe Pythia as delivering her prophecies while in a state of ecstasy, which was believed to be associated with vapors rising from the earth. Although the existence of prophetic chasm was questioned by many scholars in the past, Piccardi (2000) argues that the presence of an active fault, surface tectonic ruptures, and possible gas emissions could provide a plausible explanation for the emergence of these traditions. In this way, the geological environment is not perceived as a neutral physical setting but rather as an active factor in shaping the religious and symbolic identity of the sanctuary.

Furthermore, the author attempts to correlate historical seismic events with archaeological evidence from the region. Particular attention is given to the Helike earthquake of 373 BCE, which is considered one of the most significant historical earthquakes in the Gulf of Corinth. According to Piccardi (2000), this earthquake may have triggered movement not only along the main Helike Fault but also along the antithetic Delphi Fault, resulting in displacements and structural damage within the sanctuary. Archaeological evidence from the Sanctuary of Athena indicates that parts of the temple and altar exhibit fractures, tilting, and displacement, which may be associated with surface seismic rupture.

This approach is particularly significant because it highlights Delphi as a remarkable example of a cultural landscape in which history, religion, geology, and natural processes have interacted over time. The natural environment did not merely provide the setting for the development of the sanctuary but may also have contributed to the emergence of the prophetic tradition and the sacred character of the site itself. Natural phenomena such as earthquakes, fault activity, and possible gas emissions appear to have gradually integrated into the collective

memory and mythology of Delphi, shaping a unique cultural and religious landscape that has endured through the centuries.

This distinctive relationship between nature and the monument continues to characterize the archaeological site to the present day. The same geodynamic environment that contributed to the uniqueness of Delphi now constitutes a significant risk factor for the preservation of its monuments. Intense seismic activity, rockfalls, landslides, and weathering processes create an environment of increased vulnerability, directly affecting the protection and conservation of the archaeological site. In the context of climate change, potential changes in the frequency, intensity, and duration of precipitation, as well as changes in temperature conditions and weathering processes, should be taken into account in relation to future slope stability and the exposure conditions of the monuments (IPCC, 2022).

3.4.1 Geodynamic Instability and Natural Hazards in Delphi

The distinctive geological configuration of the Delphi region, combined with its highly active tectonic setting, favors the occurrence of natural instability processes. Geomorphologically, the area is characterized by steep slopes, extensive limestone formations, and pronounced geological discontinuities, conditions that promote rockfalls, landslides, and seismically induced mass movements. Given that the archaeological site of Delphi is situated in close proximity to the southern slopes of Mount Parnassus and directly beneath particularly steep escarpments, these conditions create an environment of elevated hazard potential for the monuments of the site.

The geodynamic instability that characterizes the region, resulting from both active tectonic processes and the morphology of the landscape, is also highlighted by Valkaniotis et al. (2011). According to the authors, the Delphi Fault constitutes one of the most significant active structures within the Corinth Rift system and is closely associated with the continuous geomorphological evolution of the area. Furthermore, the rugged topography and intense tectonic deformation affecting the limestone formations favor the development of extensive rockfalls and mass-wasting phenomena. The presence of weathered and tectonically fragmented rock masses significantly increases the likelihood of slope failures, even during relatively moderate seismic events.

Of particular importance is the fact that the principal monumental complexes of the archaeological site, including the Sanctuary of Apollo and the Ancient Stadium, are located directly in front of the main scarp of the active fault and at a short distance from the steep slopes of Mount Parnassus. This spatial arrangement renders the monuments especially vulnerable to rockfall events and seismic impacts, while the continuous action of weathering processes and gravitational material transport contributes to the gradual destabilization of the natural environment surrounding the archaeological site.

The geodynamic instability observed at Delphi is not exclusively a modern phenomenon but rather a long-standing characteristic of the Delphic landscape. Earthquakes, rockfalls, and mass movements appear to have influenced the evolution of both the natural and human environment since antiquity. This observation is directly linked to the broader perception of Delphi as a landscape in which natural processes, religious experience, and cultural memory continuously interact. In this sense, the natural environment did not merely provide the setting for the development of the sanctuary but also functioned as an active factor in shaping the historical and symbolic identity of the site.

Delphi represents a remarkable example of the inseparable relationship between natural landscape and cultural heritage. The imposing environment of Mount Parnassus and the Phaedriades Cliffs gives the site its distinctive character and enhances the visitor experience. The fact that the natural environment was not simply the backdrop against which the Oracle developed, but rather an active component of the religious experience, is reflected in the significance attributed by the ancient Greeks to the landscape itself, the sanctity of Mount Parnassus, and the sacred nature of the Castalian Spring. Another notable example is the Corycian Cave, one of the most important cult caves of antiquity, which was associated with the worship of Pan, the Nymphs, and later with Dionysian rituals. Its long-term use demonstrates that the sacred character of the region was not confined to the core area of the Oracle but extended throughout the natural landscape of Mount Parnassus. From this perspective, Delphi may be regarded as a complex cultural landscape in which the natural environment, religious practices, and monuments coexisted as interconnected elements of a unified system.

However, the same geological and geomorphological conditions that shape the distinctive character of the landscape are also associated with instability processes that may negatively affect the preservation of the monuments. The significance of these observations becomes even greater in the context of climate change. The increasing frequency of extreme weather events, intense precipitation, temperature fluctuations, and weathering processes may accelerate instability phenomena on the slopes of Mount Parnassus and further increase the vulnerability of the monuments. Consequently, understanding the geodynamic behavior of the landscape constitutes a fundamental prerequisite for the effective protection and management of the archaeological site of Delphi within the contemporary environmental context (IPCC, 2022).

It should not be overlooked that the ancient sanctuary was not merely established near an active tectonic structure but directly upon the active Delphi Fault itself. This observation is particularly noteworthy, as it suggests that the geological characteristics of the area may have influenced the selection of this specific location for the establishment of the sanctuary. The placement of the most important prophetic center of the ancient Greek world upon an active tectonic structure highlights the close relationship between the natural environment and human activity already evident in antiquity (Piccardi, 2000).

Furthermore, Piccardi (2000) reports evidence of hydrothermal activity in the area, including travertine deposits and possible gas emissions along tectonic discontinuities. These findings suggest that the geological environment of Delphi did not constitute a static natural system but rather a highly dynamic setting in which active geodynamic processes occurred. It is possible that some of these phenomena were observed by the ancient inhabitants and contributed to the development of beliefs and traditions associated with the operation of the Oracle. Within this context, references in ancient sources to vapors emerging from the ground acquire a plausible geological interpretation, without diminishing the religious significance of the prophetic process (Piccardi, 2000).

Equally significant is Piccardi's attempt to relate specific archaeological remains to historical seismic events. Particular attention is given to the Sanctuary of Athena Pronaia, where displacements and deformations of structural elements have been observed and may be associated with surface fault activation during the major earthquake of 373 BCE. The existence of such displacements provides important evidence that seismic processes not only shaped the

natural landscape of the region but also left measurable traces on the monuments themselves. This observation is especially relevant to cultural heritage studies, as it demonstrates that the interaction between natural processes and the built environment has been a continuous reality in the case of Delphi throughout its history (Piccardi, 2000).

3.4.2 Contemporary and Future Climate Change in Delphi

Projected climate changes in Greece may affect both temperature and precipitation patterns, although these changes vary depending on the region and the climatic parameter considered. In the case of Delphi, the study by Tringa et al. (2025) projects warmer conditions in the future. More specifically, a decrease in heating degree days (HDD) and an increase in cooling degree days (CDD) are projected, reflecting a general shift towards warmer conditions. At a broader level, changes in precipitation patterns are also projected for Greece (Giannakopoulos et al., 2011).

The study by Tringa et al. (2025) provides more specific information regarding the climatic conditions of Delphi. Using simulations with the regional climate model RegCM4, the study indicates a shift towards warmer climatic conditions during the 21st century, as well as a longer duration of the warm periods of the year. These projections are useful, as they contribute to understanding the possible future environmental conditions to which the archaeological site of Delphi will be exposed.

However, broader climatic changes alone cannot determine how monuments will be affected. Based on the study by Camuffo (2019), local microclimatic conditions also play an important role. Factors such as the orientation of a monument, exposure to solar radiation, air circulation, the presence of moisture, and the topography of the area can influence the conditions to which the construction materials are exposed.

3.5 Behavior of the Construction Materials of the Temple of Apollo under Environmental and Climate Conditions.

As mentioned previously, lithological diversity is identified in the case of the Temple of Apollo. Therefore, the way in which the construction materials respond should be examined by taking into account the different characteristics of each stone. Regarding Profitis Ilias limestone, it is described by de Vals et al. (2020) as a massive wackestone limestone, with a

micritic matrix and stylolitic discontinuities. From a sample collected near the ancient quarry, a density of 2.65 g/cm³ and a porosity of 1.15% were measured. These data provide a more specific basis for examining this particular material in relation to environmental conditions.

Experimental studies aimed at examining the behaviour of different lithotypes under changing environmental conditions have demonstrated the importance of the particular characteristics of each limestone. In their study, Lisci et al. (2024) examined four Portuguese limestones with different petrographic compositions and porosity through laboratory heating–cooling and freeze–thaw tests. The results of the tests showed different behaviour among the lithotypes, both in terms of changes in open porosity and their mechanical properties. Even Alpinina, which presented a low open porosity of 0.22%, showed a reduction in elastic modulus and flexural strength after the freeze–thaw cycles (Lisci et al., 2024). This result could suggest that porosity alone cannot be used to predict the behaviour of a limestone, as its petrographic and microstructural characteristics must also be considered.

The future climate changes examined in previous sections may alter the environmental conditions to which the construction materials of the Temple are exposed. Nevertheless, climate changes alone are not sufficient to determine how a particular stone will be affected, since its response depends both on its specific characteristics and on the deterioration, mechanism being examined.

By examining the results of the study by Lisci et al. (2024), useful information can be obtained regarding how limestones respond under laboratory conditions. Nevertheless, these results cannot be directly applied to the Profitis Ilias limestone. The data of the study derive from four limestones from Portugal, which have different petrographic and microstructural characteristics. Some of these characteristics show similarities with those of the Profitis Ilias limestone, such as the presence of a micritic matrix or stylolitic discontinuities in some of the examined lithotypes, without this meaning that they are directly comparable materials. At the same time, the porosity values in the studies of de Vals et al. (2020) and Lisci et al. (2024) were determined using different methods. Therefore, the results of the study by Lisci et al. (2024) can be used comparatively to understand possible deterioration mechanisms, but not to directly predict the behaviour of the Profitis Ilias limestone.

Freeze–thaw cycles are one of the mechanisms that can affect the way limestones respond to environmental conditions. Based on the study by Lisci et al. (2024), when water present within the pore network and discontinuities of the stone freezes, the formation of ice can lead to internal pressures within the material. The repetition of this process can gradually lead to the formation of microcracks and the weakening of the stone’s cohesion. However, the intensity of deterioration is not the same in all limestones, as it is influenced by characteristics such as pore size, distribution and interconnection, water content, and the mechanical strength of the material.

The results from the laboratory studies by Lisci et al. (2024) showed different changes in the mechanical properties of the four limestones after the freeze–thaw cycles. In the untreated samples, changes in the elastic modulus ranged from only –1% in Blue limestone and –5% in Lioz to –33% in Branco and –36% in Alpinina. These results can be interpreted as an indication that, even when different limestones are subjected to the same laboratory conditions, their mechanical properties may be affected in different ways.

The results of the study also demonstrated another important point: changes in the properties of limestones are not necessarily accompanied by visible signs of deterioration on their surface. Taking the untreated Alpinina and Blue samples as examples, although they underwent changes in their physical and mechanical properties, their visual condition remained intact after the freeze–thaw cycles (Lisci et al., 2024). This finding highlights that macroscopic observation alone is not always sufficient for assessing the condition of a stone material.

Beyond freeze–thaw cycles, heating–cooling cycles were also examined. In this case, different changes were again identified in the properties of the limestones examined, reinforcing the view that the way in which they respond to thermal stresses depends on the particular characteristics of each material. However, since these tests were conducted under laboratory conditions, the results can be used to understand a possible response mechanism rather than as a direct simulation of the environmental conditions affecting the Temple.

From the study by Walbert et al. (2015), in which the behaviour of three different limestones under freeze–thaw cycles was investigated, it was found that a common critical degree of saturation cannot be determined for all limestones. In the case of Savonnières limestone, deterioration was observed at a degree of saturation of 73%, while no corresponding

deterioration was observed in Lens limestone despite its higher degree of saturation of approximately 90%. The authors relate this different behaviour to characteristics such as pore-size distribution and connectivity, initial porosity, and the mechanical properties of the stone. However, since corresponding data regarding the degree of saturation, pore-network structure, and permeability are not available for the Profitis Ilias limestone, these results cannot be directly applied to this specific material. Instead, they can be used to understand the parameters that may influence the response of a limestone under freeze–thaw conditions.

In addition to the mechanisms associated with temperature fluctuations and freeze–thaw cycles, another mechanism that may affect limestone materials is salt crystallisation. When soluble salts are present within the pore network, the presence and movement of moisture may lead to cycles of dissolution and crystallisation. When crystals develop within the pores, they may in turn exert pressure on the material and contribute to the development of deterioration. However, the evolution of this process depends both on the presence of salts and moisture and on the characteristics of the pore network and the environmental conditions to which the stone is exposed (Oguchi & Yu, 2021).

The crossing of certain environmental thresholds is particularly important, as it may activate specific deterioration mechanisms. In some cases, even small changes in temperature or relative humidity may affect the behaviour of salts when environmental conditions cross specific critical thresholds. Depending on the type of salt and the environmental conditions, changes in relative humidity may influence dissolution and crystallisation processes within the pore network of the stone. Therefore, when examining this mechanism, not only the average environmental values should be considered, but also the fluctuations in the conditions to which the material is exposed (Brimblecombe, 2010).

In the case of the Temple of Apollo, no laboratory data are available in the present study regarding the presence, type, and concentration of soluble salts in the stone elements. Given that the research was based on macroscopic observation and photographic documentation, it is not possible to confirm the contribution of salt crystallisation to the observed deterioration. Therefore, salt crystallisation can be considered as a possible deterioration mechanism rather than a confirmed cause.

3.6 Documentation and Classification of Deterioration Patterns of the Temple of Apollo.

During the on-site survey and through the photographs taken at the Temple of Apollo, different forms of deterioration were identified on the stone elements. More specifically, in some areas, more than one form of deterioration was recorded on the same surface. The identified deterioration patterns are described and classified based on the terminology of ICOMOS–ISCS (2008) and their visible macroscopic morphological characteristics. The classification is based on what can be visually observed. The possible deterioration mechanisms and environmental factors that may be associated with these deterioration patterns are examined in the following sections.

Documentation and Classification of Deterioration Patterns.

The documentation of the deterioration patterns identified at the Temple of Apollo was based on macroscopic visual observation and photographic documentation conducted during the field visit to the Archaeological Site of Delphi. The aim of the on-site observation was to identify and document the visible deterioration patterns affecting the accessible stone elements of the monument.

The photographic documentation was limited to the areas of the Temple that were accessible to visitors, as no special access permission was available for restricted areas of the monument. During the field visit, stone elements showing visible deterioration patterns were photographed. The selection of the locations for photographic documentation was based on the presence of visible deterioration patterns rather than on a predefined systematic sampling protocol. The photographs were subsequently used to identify and classify the observed deterioration patterns according to the ICOMOS–ISCS terminology.

The terminology and classification of deterioration patterns were based on the internationally recognized glossary and classification system developed by ICOMOS-ISCS (2008), which is among the most widely used tools for documenting deterioration in stone monuments. The use of a standardized terminology enables the objective description of deterioration phenomena and facilitates the comparison of results with similar studies concerning cultural heritage monuments.

The analysis presented in the following sections focuses primarily on the deterioration forms identified during the field investigation and examines their potential relationship with the environmental and climatic factors affecting the Delphi region. Particular emphasis is placed on deterioration phenomena that may be influenced by the long-term exposure of construction materials to changing temperature and humidity conditions, as well as by weathering processes associated with the distinctive geodynamic and climatic environment of the area.



Figure 3. General view of the Temple of Apollo and its integration within the Delphic landscape.

Documentation and Classification of Deterioration Patterns of the Temple of Apollo.

Field observation and photographic documentation of the Temple of Apollo revealed the presence of multiple forms of deterioration and weathering affecting the surviving stone architectural elements of the monument. These deterioration phenomena do not occur in

isolation but frequently coexist on the same surface. Their classification was based on the terminology established by ICOMOS-ISCS (2008), ensuring that the description follows an internationally recognized system for documenting deterioration in stone monuments.

The principal forms of deterioration identified in the Temple of Apollo include cracking, material loss, alveolar weathering, surface recession, biological colonization, higher plant growth, discoloration, and dark surface deposits. The deterioration patterns were identified and recorded based on their visible macroscopic characteristics. Their presence alone does not allow the direct determination of the causes responsible for their development. For this reason, possible deterioration mechanisms are examined separately from the environmental and climatic factors that may influence these mechanisms, based on the relevant literature.

Cracking and Mechanical Stress

Cracking is one of the most common forms of deterioration observed in stone monuments and is associated with the development of mechanical discontinuities within the material or on its surface. During the field investigation of the Temple of Apollo, localized cracks were identified in several architectural elements, appearing as linear separations within the stone mass. According to the terminology of ICOMOS-ISCS (2008), these deterioration features are classified as cracks and constitute evidence of mechanical stress affecting the material.

The photographic documentation revealed vertical cracks in elements of the crepidoma, as well as in scattered architectural components throughout the temple. These cracks exhibit clear continuity along the stone surface and are not related to construction joints, indicating that they represent post-construction deterioration phenomena. Although in most cases the cracks do not display significant opening widths, their presence indicates a gradual reduction in the cohesion and integrity of the material.

The development of cracks in stone building materials may result from a combination of factors. In the case of Delphi, the long-term exposure of the monument to temperature fluctuations, wetting and drying cycles, and mechanical stresses associated with the distinctive geodynamic environment of the region is likely to contribute to the initiation and progression of such phenomena. Furthermore, the location of the archaeological site within an area characterized by active tectonic processes and historically documented seismicity constitutes

an additional factor that may have influenced the condition and preservation of the stone structures over time.

The significance of cracking extends beyond the immediate mechanical degradation of the material. The discontinuities created by cracks often serve as pathways for the penetration of water and moisture into the interior of the stone, facilitating the development of secondary deterioration processes. In this way, cracking may accelerate weathering mechanisms and material loss, gradually affecting the long-term preservation of the monument's architectural elements.

During the field survey of the Temple of Apollo, cracks and mechanical discontinuities were identified in various structural components of the crepidoma and the surviving architectural elements. These deterioration features manifest as vertical and oblique fractures, the opening of joints between adjacent stones, and localized displacements of structural members. According to ICOMOS-ISCS (2008), cracks constitute a form of mechanical deterioration associated with the development of internal stresses within the material or with the influence of external factors such as seismic loading, thermal fluctuations, and long-term weathering processes.



Figure 4. Deterioration patterns observed on stone elements of the crepidoma of the Temple of Apollo: (A) fracture, classified under Crack and Deformation → Crack → Fracture, and (B) fragmentation, classified under Detachment → Fragmentation, according to the ICOMOS–ISCS (2008) terminology (author's photograph, 2026).

In the photograph above, two different forms of deterioration can be identified. The area marked with the letter A is classified as a fracture, given that the discontinuity extends completely through the stone element, and according to ICOMOS–ISCS it belongs to the Crack and Deformation category. In contrast, area B is classified as fragmentation and belongs to the Detachment category. Consequently, although two forms of deterioration are identified in the same area of the monument, they do not represent the same form of deterioration.

The presence of cracks within the Archaeological Site of Delphi is of particular significance due to the intense seismotectonic activity of the region and the repeated cycles of thermal

expansion and contraction caused by pronounced daily and seasonal temperature fluctuations. These processes may contribute to the gradual widening of existing discontinuities and to the reduction of the mechanical integrity of the stone elements. Nevertheless, in the present study, the above factors can only be considered as possible contributors to mechanical deterioration, since the on-site macroscopic observation does not allow them to be identified as the specific causes of the fracture and fragmentation documented in Figure 4.

In certain cases, vegetation growth was observed within cracks and open joints. The penetration of roots into these discontinuities may accelerate the mechanical deterioration of the material through the exertion of pressure on the walls of the cracks, leading to further destabilisation of the stone elements. However, in the specific example shown in Figure 5, the presence of vegetation is recorded as an additional field observation and cannot be identified through macroscopic examination as the cause of the observed crack.



Figure 5. Vegetation growth within a crack and joint opening between adjacent stone blocks of the Temple of Apollo.

In the photograph above, two different forms of deterioration can be identified. In the area marked with the letter A, a linear discontinuity can be observed in the stone element, which, based on the ICOMOS–ISCS terminology, is classified as a crack within the Crack and Deformation category. In area B, rounding can be observed, as the original angular form of the stone edge has been reduced and appears morphologically more rounded. This deterioration pattern is classified under Features Induced by Material Loss and, more specifically, as Erosion, Rounding.

A possible interpretation for the crack identified in area A is that an architectural element may originally have rested on or transferred load to this specific part of the stone. If this was the case, the possible mechanical loading acting on this area could, over time, have generated mechanical stresses and contributed to the development of the observed discontinuity. However, this can only be considered as a possible interpretation, since macroscopic examination alone cannot safely establish such conclusions regarding the cause of the crack.

The observed cracks and mechanical discontinuities are assessed as deterioration features of moderate to high significance, as they may affect the structural integrity of the architectural elements and act as pathways for the ingress of water, salts, and biological organisms, thereby accelerating further deterioration processes.

Material Loss and Weathering.

Photographic documentation of the temple's columns and stone blocks revealed extensive material loss, manifested through rounded edges, surface flaking, localized detachments, and a generally rough stone texture.

According to ICOMOS-ISCS (2008), material loss is one of the most common forms of deterioration affecting stone monuments and is associated with physical, chemical, and biological weathering processes that act cumulatively over long periods of time.

In the Temple of Apollo, these deterioration phenomena are particularly evident on the surviving columns and architectural elements that remain exposed to environmental conditions.

The edges of many stones appear weathered, while in several cases localized detachment of small fragments and surface erosion can be observed. Long-term exposure to temperature fluctuations, wetting and drying cycles, as well as the action of wind and other atmospheric agents, may contribute to the gradual deterioration of stone materials. However, macroscopic observation alone does not allow these factors to be identified as the specific causes of the material loss documented at the Temple.

This form of deterioration is of particular interest in the context of climate change, as potential changes in temperature conditions and precipitation patterns may modify the exposure conditions of the stone elements and influence deterioration mechanisms that are sensitive to these environmental changes. However, due to the limitations of the present study, the observed deterioration cannot be directly attributed to climate change.



Figure 6. Localised weathering and material loss on a stone element of the Temple of Apollo. The photograph illustrates the development of a porous surface texture and the deterioration of the stone's superficial layer.



Figure 7. Deterioration patterns observed on a column drum of the Temple of Apollo, including alveolarization, rounding of the stone edges, and biological colonization, identified macroscopically according to the ICOMOS-ISCS (2008) terminology (author's photograph, 2026).

Alveolar Weathering

Alveolar weathering is a characteristic form of surface deterioration affecting stone monuments and is defined by ICOMOS-ISCS as the development of small to medium-sized cavities on the surface of stone, creating patterns that resemble a honeycomb structure (ICOMOS-ISCS, 2008). The phenomenon is associated with the gradual removal of material from specific areas of the stone due to differential weathering processes and results in the progressive weakening of the material's surface cohesion.

During the field investigation of the Temple of Apollo, extensive manifestations of alveolar weathering were identified in structural stones of the crepidoma and in lower sections of the

monument. The affected surfaces display numerous cavities of varying size and depth, occurring either individually or in clusters, thereby creating a highly heterogeneous surface morphology. In several cases, smaller cavities locally merge into larger weathered areas, contributing to an irregular surface morphology and visible material loss.

The development of alveolar weathering may be related to the presence and movement of moisture within the pore network of the stone. In cases where soluble salts are present, repeated wetting and drying cycles may facilitate their transport and the processes of dissolution and crystallisation. Subsequently, the formation of crystals within the pores may generate mechanical stresses and contribute to the detachment of mineral grains and material loss. At the same time, the mineralogical composition and heterogeneity of the stone may influence the way in which deterioration develops. However, no sampling or laboratory analysis was carried out to determine the presence of soluble salts. For this reason, salt crystallisation is considered only as a possible deterioration mechanism and cannot be regarded as a confirmed cause of the alveolar weathering recorded at the Temple of Apollo.

During the photographic documentation, alveolar weathering was also identified in lower areas of the monument, which may suggest a possible relationship between this deterioration pattern and the presence of moisture and repeated wetting–drying cycles, as discussed in the relevant literature (ICOMOS–ISCS, 2008; Camuffo, 2019). However, macroscopic examination alone does not allow this interpretation to be safely confirmed.

In the context of climate change, future changes in temperature and precipitation may modify the environmental conditions under which moisture-related deterioration mechanisms develop (Tringa et al., 2025; Giannakopoulos et al., 2011). However, the available evidence does not allow the future progression of the alveolar weathering observed at the Temple of Apollo to be predicted.

If alveolar weathering progresses over time, it may result in further loss of historic material and degradation of the morphological integrity of the affected stone elements. For this reason, systematic monitoring would be useful in determining whether the deterioration remains stable or progresses over time.



Figure 8. Deterioration patterns observed on a stone element of the Temple of Apollo: (A) alveolar weathering, (B) material loss and surface recession, (C) differential erosion and rounding, (D) white surface deposits possibly associated with salts, and (E) higher plant growth, identified macroscopically according to the ICOMOS–ISCS (2008) terminology (author’s photograph, 2026).



Figure 9 Surface recession, alveolarization, and biological colonization with higher plant growth observed on stone elements of the Temple of Apollo, identified macroscopically according to the ICOMOS-ISCS (2008) terminology (author's photograph, 2026).

Biological Colonization

Biological colonization is one of the most common forms of deterioration affecting stone monuments, particularly in archaeological sites that remain exposed to natural environmental conditions. According to ICOMOS-ISCS (2008), the growth of microorganisms, lichens,

mosses, and higher plants on stone surfaces or within joints can contribute not only to aesthetic alteration but also to the mechanical and chemical degradation of the construction material.

During the macroscopic examination of the monument, vegetation was identified in different areas of the crepidoma and the surviving structural elements. In some cases, plant growth was observed within the joints between stone elements. At the same time, forms of biological colonization were also identified on stone surfaces.

The roots observed penetrating gaps and discontinuities within the masonry may contribute to the development of mechanical stresses and the widening of joints and microcracks. Over time, such processes may contribute to the detachment of small fragments or to the further destabilization of already weakened stone elements. At the same time, biological colonization may influence moisture conditions on the stone surface and interact with other deterioration mechanisms (Camuffo, 2019). However, in the present study, biological colonization cannot be confirmed as the cause of specific deterioration patterns due to the limitations of macroscopic observation.

The presence of vegetation within the archaeological site acquires particular significance in the context of climate change. Changes in temperature and moisture conditions may influence biological activity and the development of biological deterioration on cultural heritage materials (Sesana et al., 2021). However, these changes alone cannot be used to predict the future development of biological colonization at the Temple of Apollo.



Figure 10. In addition to biological colonization, other deterioration patterns can also be observed on the stone elements, including cracks and localised material loss. Their coexistence within the same architectural area further illustrates that different forms of deterioration may occur simultaneously on the monument.



Figure 11. Shrub vegetation growing in close proximity to the structural elements of the Temple of Apollo. (author's photograph, 2026)

Discoloration and Surface Deposits

According to the ICOMOS-ISCS (2008) classification system, discoloration and surface deposits constitute a category of deterioration phenomena that alter the original appearance of stone without necessarily being accompanied by direct material loss.

During the macroscopic examination of the Temple of Apollo, variations in the coloration of the stone surfaces were identified, including extensive dark areas and surface deposits. At the same time, forms of biological colonization were recorded on some exposed stone surfaces.

Such discoloration and surface deposits may be influenced by atmospheric exposure, moisture conditions, particle accumulation, and biological activity. Lichen colonisation was also observed on exposed stone surfaces of the Temple. Lichens develop on external stone surfaces, while their rhizines may penetrate into the stone and interact with the substrate (ICOMOS–ISCS, 2008). However, in the present study, the exact origin of the observed discoloration and surface deposits cannot be established through macroscopic observation alone.

The photographic documentation also reveals pronounced dark discoloration and surface deposits on the columns and other stone elements of the Temple. These observations document visible alterations of the stone surfaces; however, their composition and origin cannot be determined through macroscopic examination alone. Based on the relevant literature, moisture conditions, atmospheric exposure, particle accumulation, and biological activity may be considered as possible factors associated with the development of discoloration and surface deposits (ICOMOS–ISCS, 2008; Camuffo, 2019).



Figure 12. Lichen colonisation and biological surface deposits observed on an architectural element of the Temple of Apollo.



Figure 13. General view of discoloration and surface deposits on stone elements of the Temple of Apollo, with visible cracks, discontinuities and rounding of stone edges (author's photograph, 2026).

3.7 Correlation of the Recorded Deterioration of the Temple of Apollo with the Impacts of Climate Change.

The present study constitutes a preliminary macroscopic investigation of the visible deterioration patterns affecting the Temple of Apollo and does not allow the observed deterioration to be directly attributed to climate change. The condition of the monument is the result of long-term and interacting processes and, in order to achieve a comprehensive

assessment, factors such as the natural ageing of the materials, seismic and geodynamic effects, biological activity, anthropogenic effects, local moisture conditions, and the potential amplification of certain deterioration mechanisms by future changes in climatic conditions should also be taken into account.

The field investigation at the Temple of Apollo led to the documentation of different visible deterioration patterns affecting the stone elements of the monument. However, the available data do not allow the precise determination of the causes that led to their development. The projected changes in climatic conditions at Delphi can nevertheless be examined as one of the factors that may alter the future exposure conditions of the stone materials and influence deterioration mechanisms that are sensitive to environmental changes.

The findings of Tringa et al. (2025) indicate that the Delphi region is expected to gradually transition into a warmer climatic regime during the twenty-first century. Simulations based on the RegCM4 regional climate model suggest an increase in mean temperatures and an extension of the warm periods of the year, while a substantial increase in Cooling Degree Days has also been projected.

The projected increase in temperature at Delphi may alter the future exposure conditions of the Temple of Apollo. Repeated temperature fluctuations may cause cycles of thermal expansion and contraction in the stone materials, contributing to the development of internal mechanical stresses. However, the data available in the present study do not allow the observed cracks or material loss at the Temple to be directly associated with increasing temperatures. Investigating such a relationship would require long-term on-site monitoring of microclimatic conditions and the evolution of deterioration patterns.

Changes in precipitation patterns may also affect the behaviour of moisture within construction materials. Although climate projections for the Mediterranean generally indicate a decrease in total annual precipitation, they also suggest an increase in the frequency and intensity of extreme rainfall events (IPCC, 2023; Kapsomenakis et al., 2023). The alternation between prolonged dry periods and intense rainfall may contribute to deterioration mechanisms affecting stone materials. However, the present study does not include on-site moisture measurements or long-term data that would allow these conditions to be directly associated with the specific deterioration patterns documented at the Temple.

Moisture also plays a significant role in the development of biological colonization. The presence of lichens, vegetation, and other biological organisms documented on the monument may be influenced by water availability and local microclimatic conditions. According to Camuffo (2019), moisture and relative humidity are important environmental factors influencing biological activity on monument surfaces. Consequently, future changes in temperature and humidity levels may influence the conditions that favour the development of biological colonisation on monument surfaces.

The geomorphological setting of Delphi is also of particular importance. As discussed in previous chapters, the archaeological site is located on the southern slopes of Mount Parnassus, within an area characterized by rugged topography and active tectonic processes. Therefore, the vulnerability of the Temple of Apollo depends not only on the characteristics of its construction materials but also on the broader natural environment within which it is situated.

Consequently, the deterioration patterns identified during the macroscopic examination can be examined in relation to the environmental conditions of the area, although they cannot be directly attributed to climate change. Future changes in temperature, precipitation patterns, and moisture conditions may influence the exposure conditions of the monument, while the distinctive geomorphology of the area should also be taken into account. Based on the above, systematic monitoring of the monument is important for understanding the development of deterioration patterns. At the same time, potential future changes in climatic conditions should be taken into account when planning future conservation and management strategies for the Temple of Apollo and the wider archaeological site of Delphi.

3.8 Climate – Related Exposure and Material Sensitivity of the Temple of Apollo.

The assessment of a monument's vulnerability to climate change is generally based on the examination of its exposure, sensitivity, and adaptive capacity (Sesana et al., 2020). In the present study, a complete vulnerability assessment of the Temple of Apollo is not carried out, as the available data do not allow all of the above parameters to be evaluated. For this reason, the analysis is limited to a qualitative examination of the monument's exposure to environmental and climatic conditions and the sensitivity of its stone materials.

The location of the Temple of Apollo in an open-air environment results in its direct exposure to solar radiation, precipitation, temperature fluctuations, and atmospheric conditions in general. At the same time, its location on the southern slopes of Mount Parnassus and the distinctive geomorphology of the area influence the local exposure conditions of the monument. Projected changes in temperature conditions in the Delphi region during the twenty-first century may further alter the monument's exposure conditions (Tringa et al., 2025).

The sensitivity of the Temple of Apollo to changes in environmental conditions cannot be considered uniform across all its stone elements. As previously discussed, different stone materials with different physical and microstructural properties were used in the construction of the Temple, resulting in differences in their response to environmental stresses. At the same time, the deterioration patterns identified during the macroscopic examination indicate that the state of preservation is not uniform across all surfaces of the monument. Therefore, the sensitivity of the Temple is better examined in relation to the characteristics of the individual materials and their specific exposure conditions, rather than as a uniform characteristic of the monument.

Adaptive capacity is also a parameter in the assessment of a monument's vulnerability. However, it is not systematically examined in the present study, as no data were collected regarding existing monitoring practices, conservation interventions, or the management planning of the monument. For this reason, no conclusions can be drawn regarding the adaptive capacity of the Temple of Apollo.

In conclusion, both the monument's exposure to environmental conditions and the varying sensitivity of its stone materials are factors that should be taken into account when examining the potential effects of future climatic changes on the monument. However, the available evidence is not sufficient to assess the overall degree of vulnerability of the monument, since its adaptive capacity was not evaluated and no specific assessment scale or indicator system was applied. Therefore, the present analysis represents a qualitative examination of the exposure and sensitivity of the Temple rather than a comprehensive assessment of its vulnerability.

3.9 Behavior of the Construction Materials of the Ancient Stadium under Environmental and Climate Conditions.

As mentioned previously, Parnassus limestone is the main construction material of the Ancient Stadium. In order to understand how this material behaves under different environmental conditions, its specific lithological and petrographic characteristics should be taken into account, rather than considering only its general classification as limestone. In the study by de Vals et al. (2020), samples collected near the Stadium Quarry were examined, and two different lithological subfacies of Parnassus limestone were identified. The first is described as an oolitic grainstone, consisting of ooids with sparitic cement, while the second is described as a heterogeneous and fractured wackestone containing pellets, algae, crinoids, and other biological remains. For the specific wackestone sample, a density of 2.68 g/cm³ and a porosity of 0.8% were recorded.

Parnassus limestone cannot be considered a completely homogeneous material, as different lithological subtypes have been identified (de Vals et al., 2020). The study by de Vals et al. (2020) also reports the presence of karstic features in outcrops of Parnassus limestone, which are associated with dissolution processes of the carbonate rock. More specifically, features such as lapiez, referring to small grooves and irregular cavities that develop on the limestone surface through dissolution, as well as microkarsts, which represent smaller-scale karstic features, were identified (de Vals et al., 2020). The presence of these features indicates that dissolution is a process that may affect this specific lithological type. However, their occurrence in the natural rock cannot, by itself, demonstrate that the deterioration forms observed at the Ancient Stadium result from the same mechanism.

Beyond the characteristics of the material itself discussed above, the specific exposure conditions of the Stadium should also be examined in direct relation to them. In this case, the presence and circulation of water in the area are important parameters, as water may interact with the limestone formations and their existing discontinuities. Perrier et al. (2022) point out that water circulation within the limestone formations of Mount Parnassus occurs mainly through fractures. At the same time, rockfalls have been recorded in the area of the Stadium, in the western part of the archaeological site, including in more recent periods, which led to the installation of protective barriers (Perrier et al., 2022). These findings demonstrate that the Stadium is located in an area where water circulation and rockfalls represent actual

environmental and geomorphological conditions. However, this evidence alone cannot demonstrate that the specific deterioration patterns observed at the monument were caused by these factors.

The climatic changes projected for the Delphi area may also modify the environmental conditions to which the materials of the Stadium are exposed. As previously discussed, warmer conditions are projected for the Delphi area (Tringa et al., 2025), while, at a broader level, changes in precipitation patterns are expected in Greece (Giannakopoulos et al., 2011). However, the available data on Parnassus limestone are insufficient to determine how the material itself will respond to these changes. Therefore, future climatic conditions can be considered as potential changes in the exposure conditions of the monument, but not as direct evidence that specific deterioration mechanisms will be activated or intensified.

3.10 Documentation and Classification of Deterioration Patterns of the Ancient Stadium of Delphi.

During the on-site observation and photographic documentation of the Ancient Stadium of Delphi, different forms of deterioration were identified on the stone elements of the monument. Indicatively, material loss, cracks, displacement of stone elements, biological colonisation, and localised cavity formation on the stone surfaces were observed. As in the case of the Temple of Apollo, the identification and classification of the deterioration patterns are based on their visible macroscopic characteristics and the ICOMOS–ISCS (2008) terminology, while visual observation alone does not allow the mechanisms or causes responsible for their development to be determined.

During the macroscopic examination of the stone seating tiers of the Ancient Stadium, localised displacement and disorganisation of individual stone elements were observed. At the same time, fractured and detached stone elements were identified in certain areas, while edge deterioration and material loss were also observed. These phenomena are documented based on their visible morphological characteristics and examined according to the ICOMOS–ISCS (2008) terminology.

Particular attention was given to areas where accumulations of detached stone fragments were observed, both on the seating tiers and at their base. The presence of these fragments was documented during the macroscopic examination of the monument; however, visual



observation alone does not allow the mechanisms or factors that led to their detachment to be determined with certainty.



Figure 14. General view of the Ancient Stadium of Delphi, showing its setting on the slopes of Mount Parnassus and its relationship with the surrounding rocky environment. (Author's photograph, 2026).

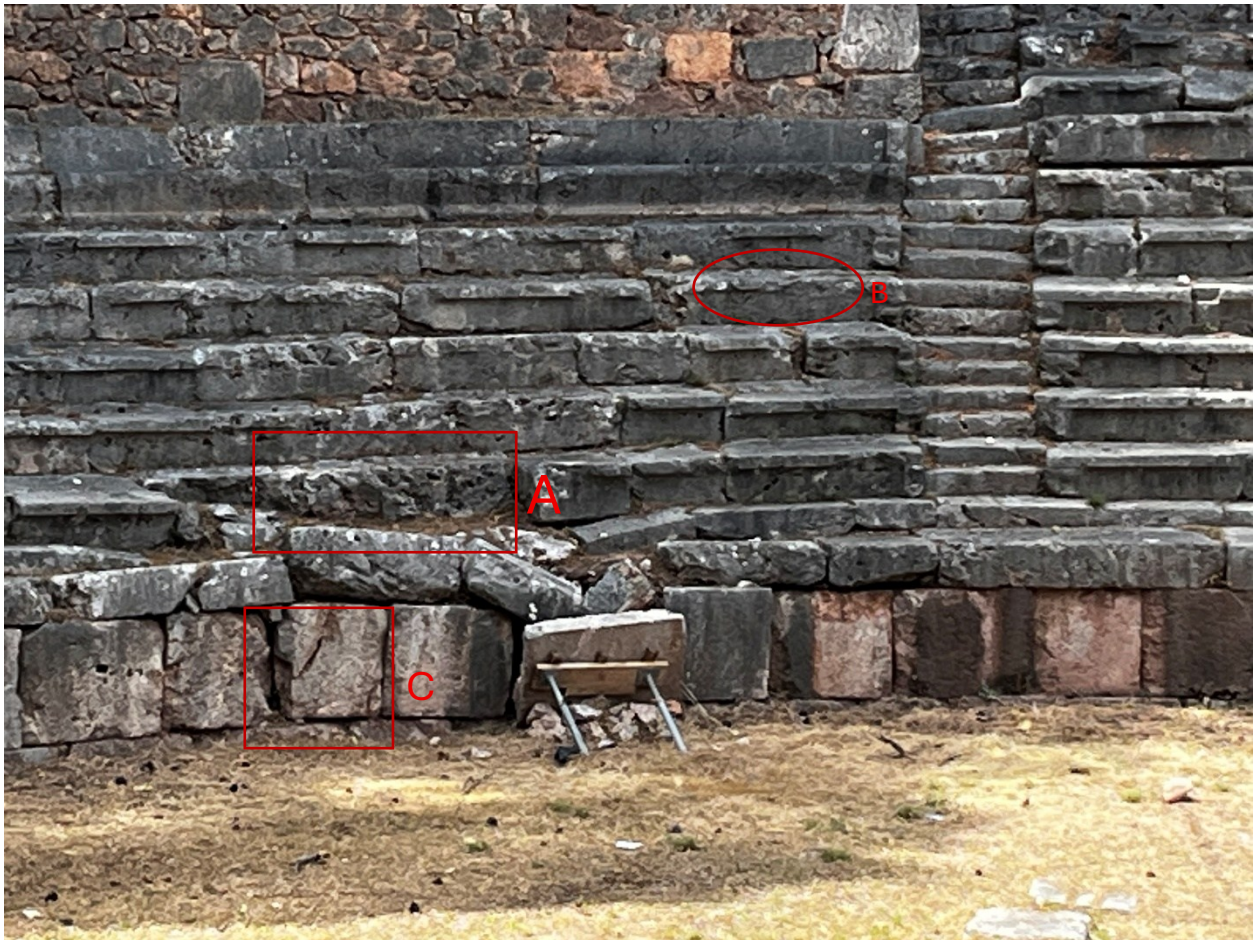


Figure 15. Deterioration patterns observed on the stone seating elements of the Ancient Stadium of Delphi: (A) alveolization, (B) erosion expressed as rounding of the edges (erosion – rounding), and (C) crack. The deterioration patterns were identified macroscopically according to the ICOMOS–ISCS (2008) terminology (author’s photograph, 2026).



Figure 16. Extensive disorganisation and localised displacement of stone elements in the seating tiers of the Ancient Stadium of Delphi, with detached stone fragments present in the central area. These observations document the macroscopic condition of the seating tiers, while visual examination alone does not allow the mechanisms or factors that led to the observed condition to be determined (author's photograph, 2026).



Figure 17. Stone elements and vegetation on the slope in the area of the Ancient Stadium of Delphi. The localised removal of loose soil material may be associated with surface runoff and washing by water, although this mechanism cannot be confirmed through visual observation alone. The presence of plants is recorded as biological colonisation (plant), according to the ICOMOS–ISCS (2008) terminology (author’s photograph, 2026).

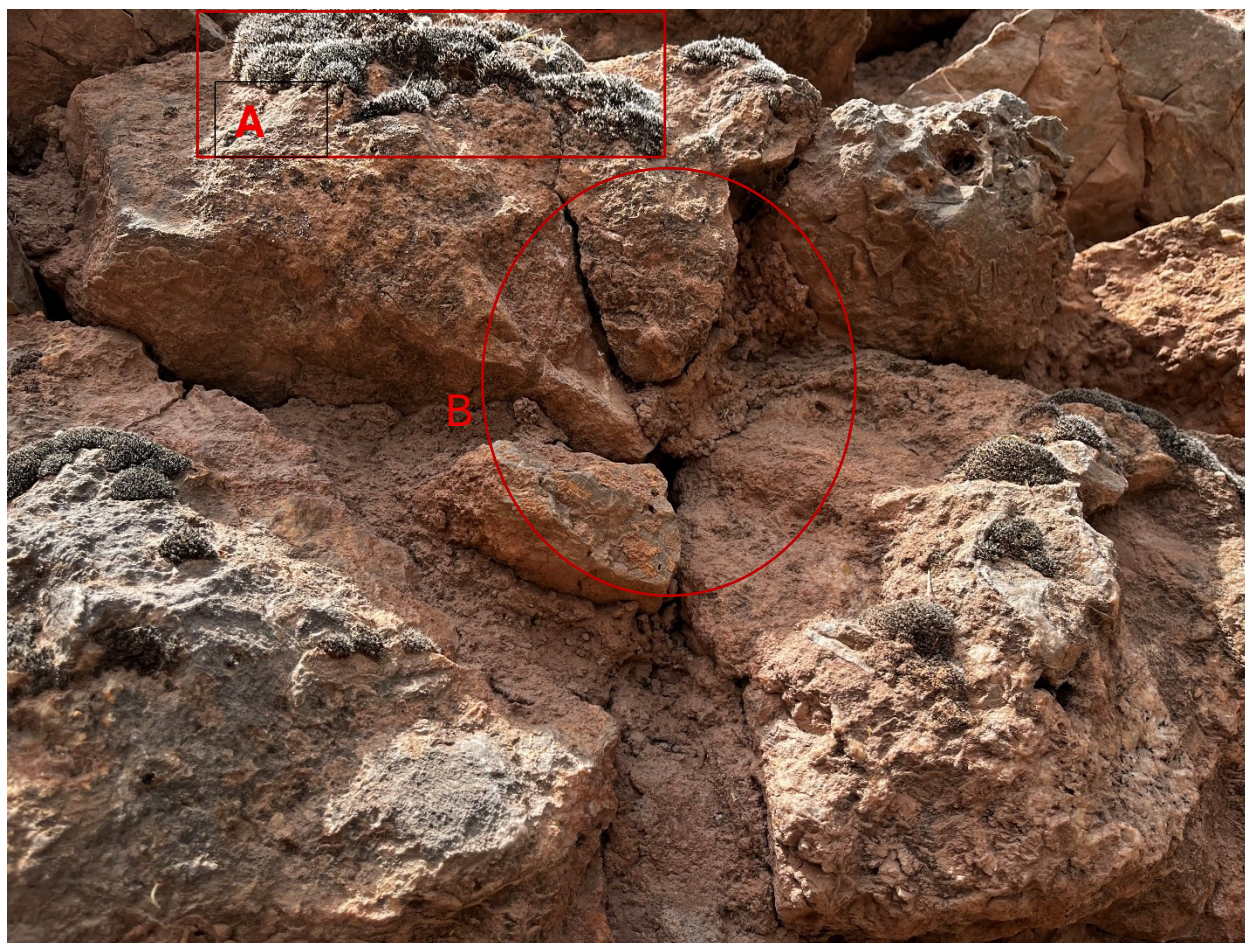


Figure 18. Deterioration patterns observed on stone elements in the area of the Ancient Stadium of Delphi: (A) biological colonization with the presence of lichen (biological colonization – lichen) and (B) crack. The deterioration patterns were identified macroscopically according to the ICOMOS–ISCS (2008) terminology, while visual observation alone does not allow the factors that led to their development to be determined (author’s photograph, 2026).



Figure 19. Pronounced alveolization in a stone element in the area of the Ancient Stadium of Delphi, characterized by the development of multiple cavities and localised material loss on the stone surface. The deterioration pattern was identified macroscopically according to the ICOMOS–ISCS (2008) terminology, (author’s photograph, 2026).



Figures 20 and 21. Macroscopic condition of the stone seating tiers of the Ancient Stadium of Delphi (top) and view of the steep limestone slopes of the Phaedriades overlooking the archaeological site (bottom). The two images illustrate the location of the monument in relation to its immediate geomorphological setting. The proximity of the steep rocky slopes represents an important parameter of the Stadium's exposure conditions, particularly in relation to the geodynamic instability and rockfalls documented in the area (author's photographs, 2026).



Figure 22. Presence of surface water runoff in the area of the Ancient Stadium of Delphi. The observation documents the presence of water and local runoff pathways in the immediate environment of the monument, which form part of its exposure conditions (author's photograph, 2026).





Figures 23 and 24. Rockfall protection measures in the area of the Ancient Stadium of Delphi (top) and view of the steep limestone slopes of the Phaedriades (bottom). The protective systems and the morphology of the rocky slopes document the geomorphological setting in which the monument is located. Rockfalls and slope instability represent important parameters of the exposure conditions of the area and have been documented in the literature for the archaeological site of Delphi (author's photographs, 2026).

4 Discussion and Comparative Assessment

During the on-site observation and photographic documentation of the Temple of Apollo and the Ancient Stadium, various forms of deterioration were identified on the stone elements of both monuments. However, their comparison should not be based solely on the presence of similar deterioration patterns, as differences in construction materials, the location of the monuments, and the conditions to which each monument is exposed should also be taken into account.

One of the differences identified between the Temple of Apollo and the Ancient Stadium concerns the stone materials used in their construction. In the case of the Temple of Apollo, a more complex lithological composition is observed, as Profitis Ilias limestone, oolitic limestone, marble, and slope breccia were used in different architectural elements (de Vals et al., 2020). In contrast, Parnassus limestone is the predominant material in the Ancient Stadium and presents different lithological characteristics compared with Profitis Ilias limestone. However, Parnassus limestone itself cannot be considered homogeneous, as the study by de Vals et al. (2020) identifies two different lithological types within this material. Although both monuments are located within the same archaeological site and are exposed to the broader environmental conditions of Delphi, this alone does not mean that the different stone materials identified in the previous sections will respond in the same way to environmental conditions, as their response also depends on their specific material characteristics. Consequently, the deterioration patterns recorded should be examined in relation to the characteristics of the materials on which they occur, rather than solely on the basis of the environmental conditions shared by the two monuments.

Beyond the differences identified in the stone materials, the two monuments also differ in terms of their location and exposure conditions within the archaeological site. The Temple of Apollo is located in the central area of the Sanctuary, on a constructed terrace, while the Ancient Stadium is situated at a higher elevation and is more directly connected to the natural slope and the rocky environment of the Phaedriades. Repeated rockfalls have been documented in the area of the Stadium, while protective systems have also been installed to address this specific hazard (Perrier et al., 2022). During the on-site observation, surface runoff and the presence of vegetation were also identified in the immediate surroundings of the Stadium. The observed surface runoff, the presence of vegetation, and the documented rockfall hazard represent

exposure conditions that differentiate the Ancient Stadium from the Temple of Apollo. The particular exposure of the Stadium to rockfall hazard is further highlighted by the study of Christaras and Vouvalidis (2010). Of the three potential rockfall trajectories assessed within the archaeological site, the trajectory crossing the Stadium was identified as the most hazardous and the most difficult in terms of retaining the falling rock blocks (Christaras & Vouvalidis, 2010).

The comparison of the two monuments in terms of the deterioration patterns recorded at the Temple of Apollo and the Ancient Stadium reveals significant similarities. In both monuments, cracks, loss of stone material, forms of erosion, and biological colonization were recorded, while patterns such as alveolization and rounding of the edges were also observed. Despite these similarities, localised displacement and disorganisation of stone elements were identified at the Stadium. These represent observations of the macroscopic condition of the seating tiers rather than individual deterioration categories according to the ICOMOS–ISCS (2008) terminology. However, the presence of similar deterioration patterns in the two monuments does not necessarily mean that they developed through the same mechanisms. As indicated in the previous paragraphs, differences in the stone materials and exposure conditions should also be considered when interpreting the recorded deterioration patterns.

The way in which stone materials respond to environmental conditions may vary depending on the characteristics of the materials and the specific exposure conditions. In the case of the Ancient Stadium, surface water runoff was recorded during the on-site observation, while Perrier et al. (2022) report that water circulation within the limestone formations of the area occurs mainly through fractures. In combination with the monument's position on the slope, these findings indicate that water represents an important parameter of its exposure conditions. In the case of the Temple of Apollo, the variety of lithological types present in its architectural elements creates a different context for examining the response of the stone materials to environmental conditions. Nevertheless, the available evidence does not allow specific deterioration patterns to be attributed exclusively to any of the factors mentioned above.

The comparative assessment of the two monuments therefore shows that the morphological similarity of the recorded deterioration patterns is not sufficient on its own to explain their development. Their interpretation requires consideration of the specific combination of material characteristics and local exposure conditions that characterise each monument.

The projected changes in climatic parameters may affect the exposure conditions of both the Temple of Apollo and the Ancient Stadium. For the Delphi area, a transition towards warmer conditions is projected during the twenty-first century (Tringa et al., 2025), while, at a broader level, changes in precipitation patterns are projected for Greece (Giannakopoulos et al., 2011). However, these climatic changes alone cannot determine how the two monuments will be affected, as the response of stone materials depends both on their characteristics and on local exposure conditions (Camuffo, 2019). Given that differences in stone materials and exposure conditions have been identified between the two monuments, the same change in a climatic parameter, such as temperature or precipitation, does not automatically mean that both monuments will be affected in the same way. Therefore, future climatic changes can be considered as factors that may alter the conditions under which deterioration mechanisms develop, without allowing the recorded deterioration patterns to be directly attributed to climate change.

5 Conservation and Protection Recommendations

Considering the overall findings of the present study, it is clear that the effective protection of the two monuments cannot be based only on addressing the deterioration patterns that are currently visible. Before specific interventions are selected, it is important to monitor their development in relation to the different stone materials and the exposure conditions of each monument. Based on these findings, the recommendations that follow begin with monitoring and assessing the condition of the monuments and then consider possible protection measures.

The macroscopic examination carried out on 11 May 2026 records the condition of the observed deterioration patterns only at that specific point in time. This limitation does not allow us to determine whether the recorded deterioration remains stable or continues to develop, or the rate at which any changes may occur. Repeating the documentation at defined time intervals would therefore allow comparison of their condition and assessment of their development over time. This is important because, as Doehne and Price (2010) point out, the extent and rate of deterioration contribute to assessing the need for an intervention and its degree of urgency.

Initially, monitoring could begin with repeated photographic documentation from fixed positions and, as far as possible, under consistent recording conditions, so that photographs taken at different times can be compared. Deterioration patterns could then be mapped using consistent ICOMOS–ISCS terminology in order to identify possible changes in their extent or distribution. In areas where cracks, material loss or displacement of stone elements have been identified, photogrammetry or other three-dimensional documentation methods could provide a more accurate geometric baseline for future comparisons. Long-term monitoring of local temperature and relative humidity could also provide environmental data that can be compared with the recorded progression of deterioration patterns (Camuffo, 2019).

In addition to photographic and three-dimensional documentation, quantitative monitoring could be applied to selected cracks in order to determine whether they remain stable or show active changes over time (Rossi & Bournas, 2023). Crack meters could be used for periodic measurements, while displacement sensors could be applied where continuous monitoring is required (Rossi & Bournas, 2023). Considering the seismicity and geodynamic setting of the Delphi area, instrumental monitoring of the seismic response of the monuments using accelerometers could also be considered. An example of such an approach can be found at the Acropolis of Athens, where an accelerometric monitoring network is in operation, including

instruments installed on the Parthenon (Institute of Geodynamics, National Observatory of Athens, n.d.), while optical-fibre sensors have also been used on the Acropolis circuit walls for monitoring small deformations (Acropolis Restoration Service [YSMA], n.d.).

If the monitoring process shows that a deterioration pattern is progressing, or if macroscopic observation is not sufficient to assess the condition of the stone, a more targeted diagnostic investigation should follow. The suitability of the diagnostic method should be assessed according to the specific problem being investigated, since a single technique may not provide all the information required for the assessment of complex forms of stone deterioration (Doehne & Price, 2010).

As mentioned above, when macroscopic examination is not sufficient to provide information on the internal condition of the stone, non-destructive techniques can be applied according to the specific problem being investigated. For example, ultrasonic testing can be used to investigate internal discontinuities, cracks or voids, while infrared thermography can be applied in areas where the presence of moisture or other subsurface anomalies is suspected (Rossi & Bournas, 2023).

In the case of the Ancient Stadium, water movement should also be taken into consideration, given that surface runoff was observed in its immediate surroundings during the macroscopic examination. Systematic monitoring and mapping of water movement could help identify runoff pathways, points of water accumulation, and areas where water comes into contact with the stone elements.

Regarding biological colonisation, which was identified in both case studies, as well as the vegetation observed in the immediate surroundings of the Ancient Stadium, these should also be monitored. Repeated photographic documentation could show whether the extent of biological growth changes over time, with particular attention to areas where vegetation develops within or near cracks and joints. Where vegetation develops within joints or discontinuities, further investigation may also be required to assess the extent of root penetration beyond what is visible through macroscopic observation.

In the case of the Ancient Stadium, particular attention should be given to rockfall hazard, as such events have already been documented and protective systems are present in the area (Perrier et al., 2022). The significance of this hazard is further supported by the study of

Christaras and Vouvalidis (2010), in which the trajectory crossing the Stadium was assessed as the most hazardous and the most difficult in terms of retaining falling rock blocks. Based on these findings, periodic inspection of both the rocky slope and the existing protective systems is considered important. If new signs of instability are identified, a targeted geotechnical assessment could be carried out in combination with three-dimensional documentation, such as UAV photogrammetry (Papaioannou et al., 2025).

Regarding the Temple of Apollo, the different lithological types identified in the monument should not be overlooked during the monitoring process (de Vals et al., 2020). The progression of deterioration could be recorded in relation to the specific lithological type on which it occurs. Over time, this could make it possible to examine whether differences emerge in the behaviour of the different stone materials under local exposure conditions.

6 Conclusion

The results of the macroscopic examination and photographic documentation show that several deterioration patterns were identified in both case studies, including cracks, material loss, alveolisation, rounding and biological colonisation. In the Ancient Stadium, localised displacement and disorganisation of stone elements were also recorded. Therefore, despite the differences between the two monuments in terms of their materials and exposure conditions, they present several deterioration patterns in common.

At the same time, the results of the study indicate that the deterioration patterns identified cannot be assessed in relation to a single environmental factor. Factors such as the presence and movement of water, temperature variations, biological activity and vegetation, as well as slope instability and local exposure conditions, may contribute in different ways to the progression of deterioration. Their influence should also be considered in relation to the characteristics of the stone materials on which the deterioration occurs. In the case of the Ancient Stadium, particular importance is also given to the surface runoff recorded during the field examination and to the geodynamic setting of the area, including the documented rockfall hazard.

In relation to climate change, the present study cannot establish that the deterioration patterns identified in the two monuments were caused by climatic change. However, projected changes in climatic parameters may modify the future exposure conditions of the monuments and, consequently, the conditions under which deterioration mechanisms develop and progress. This is particularly relevant at Delphi, where the archaeological site is closely connected to its surrounding natural environment. For the Delphi area, a transition towards warmer conditions is projected, while changes in precipitation patterns are also projected at the broader Greek scale. The effects of these changes cannot be expected to be the same for all stone materials, as their response also depends on their specific characteristics and local exposure conditions.

In conclusion, through the comparative assessment of the Temple of Apollo and the Ancient Stadium, the present study concludes that the visible morphology of a deterioration pattern is not sufficient on its own to understand how it develops or progresses. Although the two monuments are located within the same archaeological site and present several deterioration patterns in common, differences were identified both in their stone materials and in their local

exposure conditions. Therefore, the presence of similar deterioration patterns does not necessarily mean that the same deterioration mechanisms are acting in both monuments. The present study contributes not only to the documentation and classification of the visible deterioration patterns but also seeks to examine their relationship with the characteristics of the stone materials and the specific local exposure conditions affecting each monument. The findings therefore highlight that, even within the same archaeological site, the condition and future development of each monument need to be examined individually, through the interaction between its material characteristics and its local exposure conditions.

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ΥΠΕΥΘΥΝΗ ΔΗΛΩΣΗ ΣΥΓΓΡΑΦΕΑ

Δηλώνω ρητά ότι, σύμφωνα με το άρθρο 8 του Ν.1599/1986, η παρούσα εργασία αποτελεί αποκλειστικά προϊόν προσωπικής μου εργασίας, δεν προσβάλλει κάθε μορφής δικαιώματα διανοητικής ιδιοκτησίας, προσωπικότητας και προσωπικών δεδομένων τρίτων, δεν περιέχει έργα/εισφορές τρίτων για τα οποία απαιτείται άδεια των δημιουργών/δικαιούχων και δεν είναι προϊόν μερικής ή ολικής αντιγραφής, οι πηγές δε που χρησιμοποιήθηκαν περιορίζονται στις βιβλιογραφικές αναφορές και μόνον και πληρούν τους κανόνες της επιστημονικής παράθεσης.