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KALAPODI, GREECE: THE PROBLEM OF FROST AT THE ARCHAEOLOGICAL SITE AND THE IMPLEMENTATION OF THE TRIQUETRA PROGRAMME

Artemios OIKONOMOU[*, **] & Themistoklis BILIS[*]

[*] *German Archaeological Institute - Athens, Greece.*
[**] *University of West Attica - Department of Conservation of Antiquities and Works of Art - Athens, Greece*
Corresponding author: artemios.oikonomou@dainst.de

EXTENDED ABSTRACT

Il sito archeologico di Kalapodi, situato in Fthiotis, nella Grecia centrale, utilizzato ininterrottamente dal periodo preistorico fino all'epoca bizantina, è stato ampiamente scavato e studiato dall'Istituto Archeologico Tedesco di Atene. Kalapodi è uno dei santuari più importanti della Grecia centrale e gli scavi hanno portato alla luce due complessi templari paralleli e altre strutture che dimostrano sia lo sviluppo dell'architettura sacra dell'antica Grecia sia delle attività rituali, soprattutto nel primo millennio a.C. Tuttavia, le condizioni climatiche che influenzano i materiali da costruzione, in particolare il gelo, rappresentano un serio problema per la conservazione del sito. Per questo motivo, il sito di Kalapodi è uno degli studi pilota del Programma TRIQUETRA, finanziato dall'accordo quadro *Horizon Europe* dell'UE (GA 101094818) (Ioannidis *et alii*, 2024).

Questo studio mira a individuare strategie di conservazione attraverso analisi scientifiche e monitoraggio delle condizioni meteorologiche.

Il clima a Kalapodi è di tipo mediterraneo, con estati relativamente calde e secche, mentre l'inverno è fresco e umido, con frequenti gelate che rappresentano una minaccia importante per le strutture in pietra del sito con un microclima influenzato principalmente dalle montagne circostanti, come il vicino Parnaso (massima elevazione circa 2500 metri). I cicli di gelo e disgelo, comuni nelle stagioni di transizione, sono responsabili di stress meccanici sui materiali porosi come il calcare, causando un deterioramento significativo. Inoltre, l'aumento delle precipitazioni, combinato con periodi più lunghi di siccità a causa dei cambiamenti climatici, intensifica indirettamente il deterioramento del monumento.

Come parte del Programma TRIQUETRA, è stato condotto uno studio approfondito sia sul clima che sui materiali utilizzati a Kalapodi. Per valutare le tendenze climatiche passate e future, sono stati analizzati dati osservativi, registrazioni storiche del clima e modelli climatici regionali (RCM). I risultati indicano un aumento significativo della temperatura, con proiezioni che suggeriscono un rischio crescente di impatti microclimatici sul patrimonio culturale.

Sono state quindi effettuate analisi approfondite sui materiali delle pietre di due complessi templari (quello classico e quello arcaico) del santuario. Oltre alla caratterizzazione dei materiali edilizi, i campioni sono stati sottoposti a test di resistenza al gelo e a processi di invecchiamento artificiale. I risultati hanno mostrato che, sebbene i calcari dimostrino una buona durabilità, soffrono comunque di danni considerevoli causati dal gelo, con erosione superficiale ed indebolimento strutturale. In alcuni campioni sono stati applicati materiali di consolidamento a base di nanotecnologia per valutare il loro comportamento sotto le stesse condizioni di prova. I primi risultati indicano che, mentre questo trattamento offre una certa resistenza ai danni da gelo, non migliora significativamente la durabilità delle pietre contro l'azione del sale e dell'umidità.

Inoltre, è in corso la costruzione di una replica su larga scala di una parte importante dei gradini e dello stilobate del tempio settentrionale, utilizzando tecnologia CNC e pietre calcaree moderne con proprietà fisiche simili a quelle originali. Questa struttura sperimentale permetterà di valutare in tempo reale gli effetti dei fenomeni atmosferici e l'efficacia delle strategie di conservazione per ridurre i danni causati dal gelo. Per questo motivo, è stato installato anche un sistema di monitoraggio meteorologico sul sito, che raccoglie dati locali di temperatura e umidità, consentendo di comprendere meglio le variazioni microclimatiche.

Infine, è stato realizzato un nuovo sistema di protezione dal gelo, che incorpora elettrodi riscaldati e termometri di rilevamento. Questo sistema, sviluppato internamente, si attiva automaticamente quando la temperatura raggiunge i 3°C, prevenendo la formazione di brina sulla replica. Il funzionamento di questo sistema sarà monitorato tramite telecamere termiche a luce visibile, per valutarne l'efficacia nel lungo periodo. Sono in corso anche ricerche per ottimizzare l'applicazione di *nanocoating* protettivi, che migliorino la resistenza delle pietre alle condizioni atmosferiche.

In conclusione, il sito di Kalapodi rappresenta un importante caso di studio sull'impatto dei cambiamenti climatici, soprattutto nel corso della stagione invernale, quando si verificano fenomeni estremi.

L'implementazione del Programma TRIQUETRA sottolinea quanto sia fondamentale un approccio interdisciplinare alla conservazione del patrimonio culturale, combinando scienza dei materiali, monitoraggio e modellazione climatica, e strategie di tutela per affrontare i problemi legati al cambiamento climatico e garantire la protezione dei monumenti in futuro.

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ABSTRACT

In central Greece, in today's Fthiotis, where in antiquity Phokis bordered eastern Lokris and Boeotia, there is a sanctuary that is one of the most important of ancient Phokis. Systematic excavations were carried out in the sanctuary in the second half of the 20th century, under the direction of the German Archaeological Institute and they continue to this day. As part of the TRIQUETRA programme an integrated methodological model to protect archaeological remains at Kalapodi from frost is proposed. The TRIQUETRA project (EU HE research and innovation programme under GA No. 101094818) aims at creating an evidence-based assessment platform that allows precise risk stratification, and also creates a database of available mitigation measures and strategies, acting as a Decision Support Tool towards efficient risk mitigation and site remediation (Ioannidis *et alii*, 2024). This paper will present climatic data of Kalapodi together with materials analysis of the building materials of the sanctuary highlighting the frost problem.

Keywords: *Kalapodi, Central Greece, climate change, Triquetra project, stone materials.*

INTRODUCTION

The site

At Kalapodi in central Greece, in today's Fthiotis, which in antiquity bordered eastern Lokris and Boeotia (Fig. 1), there is a sanctuary that is one of the most important of ancient Central Greece (Niemeier, 2013; Sporn, 2021; Sporn & Grigoropoulos, 2024). The ancient sanctuary is situated at an altitude of about 310 m and at a distance of about 1,300 m east of the settlement Kalapodi in Fthiotida on the southern slope of the low hill Koummarorrachi, which is part of the southern foothills of the Kallidromo mountain (1,399 m) (Fig. 2) (Galanou *et alii,* 2017). At a short distance, south of the excavation, the small valley of Alarginos stream is formed, located between the mountains of Kallidromo and Chlomos Mountain (1,079 m). The waters of Alarginos, like other streams, follow an eastern course and are concentrated in the catchment area of eastern Lokris and after about 13 km end up in the N. Euboean Gulf. The provincial road, which connects Atalanti with Delphi, runs parallel to the stream and passes a short distance from the excavation, at the site of Ag. Apostoloi, where the homonymous chapel is located (Galanou *et alii*, 2017).

Systematic excavations were carried out in the sanctuary only in the second half of the 20th century, under the direction of the German Archaeological Institute and they continue to this day. The sanctuary was in the same region as the famous pan-Hellenic oracle of Apollo at Delphi. According to the excavators the sanctuary was possibly another oracle of Apollo, the famous one of Abae. Recent discoveries have also testified monuments related also to the cult of Artemis (Sporn & Grigoropoulos, 2024).

Fig. 1 - Kalapodi site in central Greece (38°38'11"N 22°53'44"E).

The results of the excavations were impressive, especially on the issue of the continuity of worship from prehistoric times to the Roman era. The architectural remains were also significant for the evolution of ancient Greek architecture. Temples of different periods, with various types of structure and materials, are a testament to the gradual development of ancient Greek temple architecture over time. The first large scale building of a cult site all over Greece was made there in Mycenean times, while gradually from the Geometric period and in the Archaic period a monumentalization took place. Finally, during the Classical period Kalapodi sanctuary follows the systematic mode of expression based on the rules of the period. These cult buildings are arranged in two parallel monumental units, a northern and a southern one. After excavation, the architectural remains had for years been protected either under embankments (northern monumental unit) or under a low and temporary roof shelter (southern monumental unit). Many excavated sections were backfilled. Even the ruins that were under the protective canopy were virtually inaccessible, partly because they were under geotextiles, and partly because the canopy itself was particularly low and dangerous to the personnel and the scientists (Fig. 3 upper photo).

The subsoil in the area where the sanctuary was built is characterized by pliocene formations, consisting of marls, clays, sandstones, conglomerate rocks, margaic limestones and other lake deposits (Fig. 4) (Dounias, 2017). There is intense seismic activity in the area, as it is very close to the fault zone of Atalanti (Palybou 2001; Galanou *et alii*, 2017). In this direction and in the framework of TRIQUETRA programme (Ioannidis *et alii*, 2024) in 2023 a seismic assessment of the archaeological site has been completed by Prof. S. Martino and the Sapienza Università di Roma – Research Centre for Geological Risk (CERI).

Fig. 2 - Kalapodi site plan with various visible ruins. The red dot indicates the place where the temple replica has been constructed (site plan P. Gourgouleti, DAI-Athen)

Presentation Works

In 2017, the German Archaeological Institute had started working on a plan for the cultural heritage management and the presentation of the southern temple complex. In autumn 2018, the maintenance and presentation works were almost completed. In 2023 the temporary presentation of the northern temple was also completed. The shape of the soil was restored, and the ruin of the archaic temple now emerges naturally from the soil, just as it was the case in Greek archaic architecture (Sporn & Grigoropoulos, 2024; Bilis & Sotiropoulos, 2024).

According to the architectural study, four chronological phases remain visible and intertwined with each other, shedding considerable light on the historical evolution of the sanctuary from Geometric times to the Roman era (Fig. 5). Indeed, with the work of marking the Geometric temple proposed with replicas of raw bricks, for the first time the scale of this great temple is so well understood. The pediment was proposed, after its systematic research, to be exhibited as an exhibit of major importance at the place where it was found (Bilis, 2021a; 2021b; Bilis & Sotiropoulos, 2024).

Climate conditions of the wider area of Fthiotis and Kalapodi

The region of Fthiotis features a Mediterranean climate with noticeable continental influences. This climate is generally characterized by warm, dry summers and cool, wet winters, though the geographical diversity of the area introduces significant local variations. The low-lying areas, such as the plains where Kalapodi is located, differ from the mountainous zones, which experience colder winters and higher precipitation levels.

Summers in Fthiotis are typically hot, with temperatures ranging from 25°C to 35°C. During heatwaves, the temperatures can climb even higher. Winters, on the other hand, are relatively mild in the lowland regions but colder in the uplands. Average winter temperatures range from 0°C to 10°C, and frost is a frequent occurrence, especially in the valleys and other areas sheltered from wind. Precipitation is most common during autumn and winter, with the region receiving an average annual rainfall of 600-800 mm. The mountainous areas often see more rainfall due to orographic effects, and occasional

Fig. 3 - Kalapodi sanctuary. The ruins of the site before (upper photo) and after (lower photo) presentation works (DAI-Athen archive)

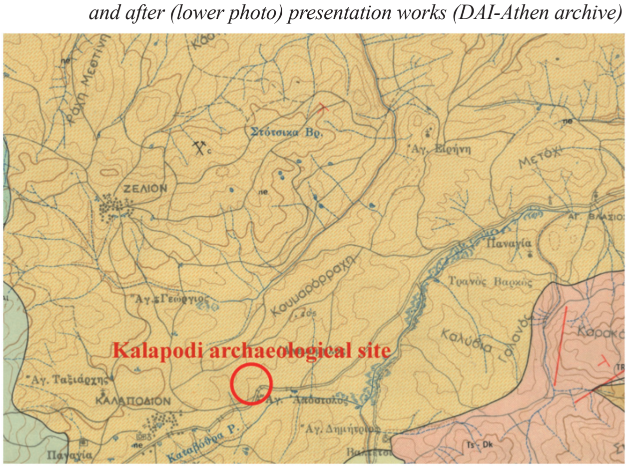

Fig. 4 - Geological map of the Kalapodi region. The area (yellow colour) consists mostly of marls, clays, gravels, sandstones, conglomerates and marly limestones. The area on the right corner (pink colour) contains compact dolomites usually white and sometimes grey (Hellenic Survey of Geology & Mineral Exploration (H.S.G.M.E.)

snowfall is common in these higher elevations.

Humidity levels are moderate, with higher readings during the cooler months when precipitation increases, and evaporation rates decrease. Winds in the area are generally mild to moderate, influenced by seasonal systems such as the

Fig. 5 - Kalapodi sanctuary restoration works today (DAI-Athen archive)

Etesian (Meltemi) winds during the summer and southerly or easterly winds during winter storms.

The local climate at the Kalapodi archaeological site, positioned in a low-lying area surrounded by hills, is slightly moderated compared to the surrounding region. It is characterized as continental with the average temperature per year ranging from 8.3°C to 25.9°C. The highest temperatures occur during the summer months and sometimes reach 40°C, while the lowest occur from December to mid-March and can reach −-2°C. In 2014, a total of 15 days of frost were recorded. The average daily rainfall is generally low and ranges from 3 mm to 36.6 mm. In 2014 overall rainfall reached 627.7 mm, with the highest height recorded in the month of December, which reached 131 mm in one day. Winds blow in the SE, E-SE direction, with an average speed ranging from 1.3-1.8 km/h and an average maximum of 33.8-51.5 km/h (Galanou *et alii*, 2017).

During winter, the site often experiences frost due to radiation cooling in its valley-like geography, where cold air masses coming from Parnassus mountain on the west become trapped. Freeze-thaw cycles, which are particularly damaging to porous materials like limestone and marble, are a recurring issue during transitional seasons such as early spring and late autumn. Summers at Kalapodi are marked by high temperatures, which can cause thermal stress to the archaeological materials, leading to the desiccation of exposed surfaces and contributing to the weathering of stone structures. Extreme weather events, such as heavy rainfall, pose additional risks of erosion and waterlogging, which can disturb the archaeological layers and increase the vulnerability of the site.

Past environmental data and simulations

The emerging and gradual changes in temperature, precipitation, wind intensity, atmospheric moisture, as well as the occurrence of extreme events as manifestation of climate change, are well recognized to impact cultural heritage (CH) sites (Collete, 2007; Sesana *et alii,* 2021).

To assess climate change-related effects and risks in CH sites, climate parameters and induced risks should be linked to processes impacting cultural heritage. For example, changes in atmospheric moisture due to heavy rainfall may affect soil chemistry, cause groundwater fluctuations, and increase wetness. These factors can alter structural changes in porous building materials due to prolonged exposure to moisture and changes in the pH of water. Temperature variations may further threaten the integrity of cultural heritage sites by causing thermal stress that accelerates the deterioration of facades. Freeze-thaw cycles also contribute to frost damage in historical structures, compromising their stability. Wind is another factor which indirectly can cause damage to structures by increasing the penetration of moisture into porous materials through wind-driven rain and possibly transported insoluble salts leading to surface erosion. Beyond these physical threats, climate change and especially changes in water/moisture may foster biological effects that impact monuments such as increased mould growth (for detailed description of climate change risks and impacts on cultural heritage please see Collete, 2007).

To work towards the identification of potential damages related to Kalapodi, relevant climate data for the assessment of climatic information associated with Kalapodi during the recent past period. In particular, observational, E-OBS (gridded observational), and model data were examined (Zanis *et alii*, 2023). The climatic information is based on three different types of data:

- Local weather stations with long meteorological records at the proximity of Kalapodi.
- Land-only gridded observational data for several meteorological variables over Europe.
- Ensemble of high-resolution Regional Climate Models (RCMs).

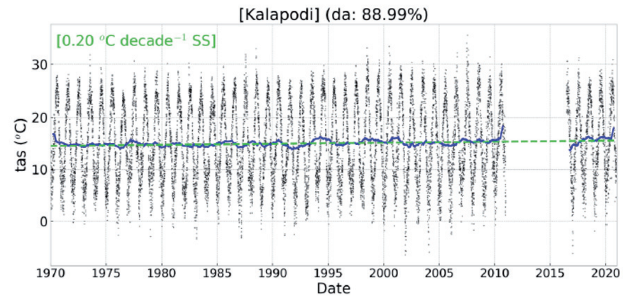

Fig. 6 - Surface-temperature daily time series (black circles) at Kalapodi over the period from 1970 to 2020. The blue line shows the one-year centered moving average. The greed dashed line and green text inside the brackets depict the Theil-Sen trend and the Mann-Kendall statistical significance at the 95% confidence level (Zanis et alii, 2023)

The E-OBS v26.0e gridded observational data were obtained from the ECA&D at a horizontal resolution of 0.1o × 0.1o. It comes as an ensemble dataset constructed through conditional simulation processes and observational data from weather stations all over Europe as described in Haylock *et alii* (2008) and Cornes *et alii* (2018). Observational data from weather stations exhibit sufficient data availability during the 1970-2020 period for Kalapodi and the E-OBS results for surface temperature are shown in Fig. 6. On the same figure the one-year centered moving average is presented, as well as the Theil-Sen trend calculated from the one-year average series, and the Mann-Kendall statistical significance at the 95% confidence level characterized as "SS" for statistically significant. Interestingly, Kalapodi exhibits statistically significant positive surface-temperature trends ranging from 0.17 to 0.62 °C decade^{-1}, in agreement with observed global warming during the recent past period.

Furthermore, the climatic information from the ensemble of EURO-CORDEX RCM simulations during the recent

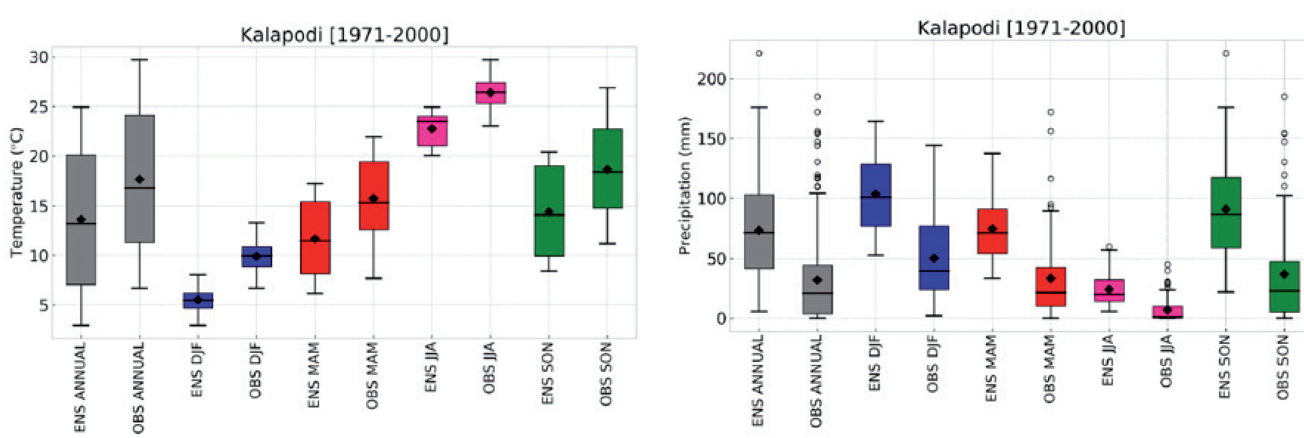

Fig. 7 - Whisker plots of surface temperature (oC) (left) and precipitation monthly sum (mm month-1) (right) for the ensemble of EURO-CORDEX RCMs (ENS) and observations (OBS), for annual (grey), DJF (blue), MAM (orange), JJA (pink), and SON (green), for Kalapodi over the period 1971-2000 (Zanis et alii, 2023)

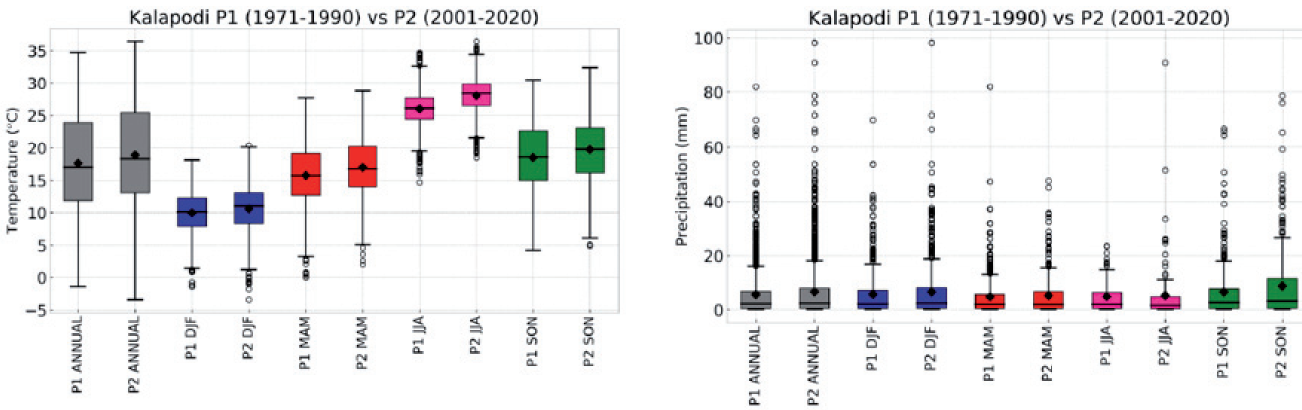

Fig. 8 - Whisker plots of observed surface temperature (oC) (left) and observed daily precipitation (mm day-1) (right) during the periods P1 (1971-1990) and P2 (2001-2020), for annual (grey), DJF (blue), MAM (orange), JJA (pink), and SON (green) for Kalapodi (Zanis et alii, 2023)

past period and their evaluation based on observations are depicted in the following whisker plots1 (Fig. 7, 8) including available climate parameter for the RCMs ensemble (ENS) and observations (OBS) in both annual and seasonal (December January February - DJF, March April May - MAM, June July August - JJA, September October November - SON) basis. To select a common period with both observations and ensemble data available before the RCP scenarios periods (starting in 2005), the period from 1971 to 2000 is selected.

Overall, there is a good agreement between the ENS and OBS datasets for surface temperature. Regarding precipitation, the RCM ensemble exhibits higher values than observations. Generally, the RCMs ensemble captures satisfactorily the observed climate parameters during the recent past period 1971-2000. Any discrepancies seen between the observed and modeled values is subject to model uncertainties (resolution, parametrizations, etc.) and different characteristics (elevation, land type) between the exact location of Kalapodi and the selected model nearest grid point which is in Thiseio, Athens 103 km away.

Furthermore, the observed surface temperature and daily precipitation are presented in Fig. 10 for Kalapodi between two past long periods from 1971-1990 and 2001-2020 on both annual and seasonal basis in order to assess possible changes.

Following the approach of Tringa and Tolika (2023), the Heritage Outdoor Microclimate Risk (HMRout) and the Predicted Risk of Damage (PRD) indices were applied to evaluate the suitability of microclimates and quantify the damage risk. Using the observational data from the recent past, the years characterized by Minimum-Low, Moderate-Medium, and High-Maximum risk for the temperature parameter were calculated for the periods 1971-2000 and 2001-2020 (Fig. 9). In general, the findings indicate an increased risk of microclimate impact on cultural heritage during the period 2001-2020. This is deduced from the reduction in years characterized by Minimum-Low risk and the increase in years with Moderate-Medium and High-Maximum risk. It's crucial to emphasize that the increase in temperature is closely linked to this elevation in risk. More specifically, Kalapodi exhibits an increase in years with High-Maximum risk (38%) and a 37% increase in years with Moderate-Medium risk. Furthermore, the PRD index indicates that the likelihood of damage to cultural heritage due to increasing heat stress on the inorganic material increased on average by 31% at Kalapodi. These findings emphasize the vulnerability of cultural heritage to the impacts of climate change, underscoring the critical need for additional research on future climatic conditions. This is work in progress, by assessing the multi-model ensembles of RCM simulations for three different scenarios (RCP2.6, RCP4.5 and RCP8.5) to evaluate the future HMRout and PRD indices for two climatic variables, Temperature and Relative Humidity. According to the literature, a potential change in these two climatic parameters could have significant impacts on monuments (Fatorić & Seekamp, 2017; Camuffo, 2019). Analyzing these two critical climate parameters will provide a more comprehensive understanding of how variations in temperature and relative humidity may affect the resilience of materials and the overall preservation of cultural heritage sites constructed from stone.

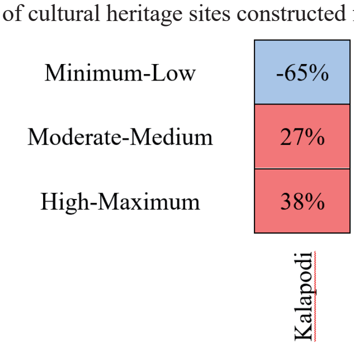

Fig. 9 - For each risk category the differences between the early (1971-2000) and late (2001-2020) past period for Kalapodi (The percentages represent gain or loss among the total years) (Zanis et alii, 2023)

Snow cover in Kalapodi and the problem of frost can be influenced by a combination of both meteorological and environmental factors. The extent and duration of snow accumulation at a site depends on temperature fluctuations, wind patterns, and subsequent weather conditions. According to The German Aerospace Center (DLR), partner of the Triquetra project, and the gathering of past climatic data, the mean value of snow cover in a wide area (approx. 260 km^2) including Kalapodi archaeological site and various mountains such as Parnassus starts in mid of September (apparently in the higher altitudes) until end of April with the highest snow cover happening in January/February (Fig. 10).

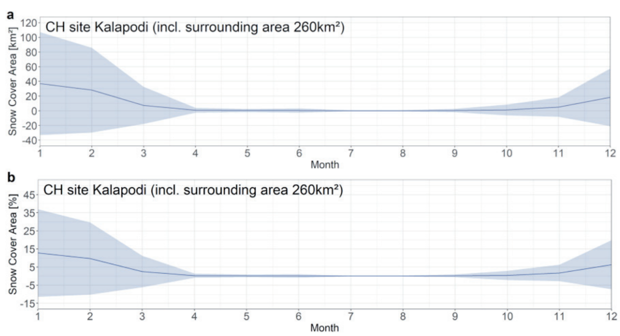

Fig. 10 - Mean snow cover area in km² (a) and % (b) derived from daily snow cover extent for the CH site Kalapodi based on monthly means (1=Jan to 12=Dec) for the period 2000-2022 (DLR)

In addition, in the framework of Triquetra implementation, DLR performed snow cover analysis at Kalapodi site using modeled snowfall and Earth Observation (EO) parameters which revealed critical insights into the future of snow cover under varying climatic scenarios. The analysis indicated that the extent and duration of the snowfall are mostly influenced by variations in temperature and wind. Subsequent weather conditions, such as rainfall and melting periods due to temperature rise, can further reduce snow cover, highlighting the complex relationship of climatic elements affecting snow and the subsequent frost (Mitterwallner *et alii*, 2024; "Change in snow depletion pattern in a river basin of Arunachal Pradesh under projected climatic scenarios", 2017).

The analysis included the investigation of monthly snow cover and snowfall data for a period of 22 years under various Representative Concentration Pathways (RCPs) which facilitated a comparative assessment for future climatic scenarios. The projections under RCP4.5 and RCP8.5 indicate a substantial decrease in snowfall by the years 2050 and 2100, which is mostly evident at RCP8.5 representing high emissions scenario. This decrease in snowfall can be attributed to the general rise in temperature which intensifies melting i.e. the transition from solid to liquid precipitation, which in that way may reduce the amount of snow cover both in terms of duration and depth (Mitterwallner *et alii*, 2024; Steger *et alii*, 2012; Krasting *et alii*, 2013).

Application of the TRIQUETRA Programme

The wider region of Fthiotis, including Kalapodi, the last decades is increasingly affected by climate change, which has increased various environmental challenges. Temperature extremes, following the same pattern almost in every place in Greece, are becoming more obvious, with unpredictable longer frost events in the winter and more frequent heatwaves during the summer period. In addition, the rainfall has been increased and extreme precipitation events can lead indirectly to significant erosion and deterioration of the monuments. Simultaneously, extended dry periods as a result of hotter and longer summers, intensify dryness and compromise the integrity of the use of protective coatings or conservation treatments applied to the archaeological remains.

The Kalapodi site suffers from frost phenomena which, together with the humidity/rainfall, pose a constant danger to the site's materials. The porosity of the materials traps moisture and water and due to frost can cause internal damages which, in combination with the vulnerable structural materials, causes decay problems. Currently this problem is solved by seasonal covering with geotextile and insulation panels (Fig. 11). Due to climate change, in the future all these problems will become intensified.

Fig. 11 - The ruins of the site are protected during winter by seasonal covering with geotextile and insulation panels. Photo: Ch. Vaporakis, DAI Athen

As a first step to understand how frost is affecting the building materials of the site, we performed an extensive chemical and mechanical analysis of the materials of the monument. The primary construction materials used in the Kalapodi site were locally available stone, terracotta, wood, and metals. For instance, at the archaic temple (south monumental complex), limestone was employed for temple pediments, while wood was commonly used for columns and entablatures, reflecting a blend of stone and organic materials in the construction. Terracotta was widely used for roof tiles and decorative elements, such as simas and acroteria. The site also reveals instances of reused materials, where

Code number	Material	Origin
KL1	Stone-St	Classical Temple Limestone
KL2	Stone-St	Archaic Temple, Soft Limestone
KL3	Stone-St	Archaic Temple, Hard Limestone 1
KL4	Stone-St	Archaic Temple, Hard Limestone 2
KL5	Stone-St	Grey limestone Foundations
KL6	Stone-St	Hellenistic Building
KL7	Stone-St	Hellenistic Building
KL8	Stone-St	Hellenistic Building
KL9	Stone-St	Hellenistic Building
KL10	Stone-St	Classical Temple
KL11	Stone-St	Classical Temple
KL12	Stone-St	Classical Temple
D1	Wallpainting/Plaster-WP&P	Hellenistic Building / Black paint
D2	Wallpainting/Plaster-WP&P	Hellenistic Building / White paint
D3	Wallpainting/Plaster-WP&P	Hellenistic Building / red paint
D4	Wallpainting/Plaster-WP&P	Hellenistic Building / Blue paint
D5	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / yellow paint
D6	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / red paint
D7	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / black paint
D8	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / white paint
D9	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / paint imitation of conglomerate
D10	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / black paint
D11	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / black paint
D12	Wallpainting/Plaster-WP&P	Warehouse. Archaic temple / green paint
D13	Wallpainting/Plaster-WP&P	Warehouse. West of Archaic temple / yellow paint
D14	Wallpainting/Plaster-WP&P	Warehouse. North of classical temple / red paint
D15	Wallpainting/Plaster-WP&P	Warehouse. North of classical temple / yellow paint
K4	White plaster-WP	Adyton SW corner
K10	Masonry mortar-MM	Roman Masonry
K2	Mudbrick-MB	Late Geometric Temple NW Niche
K5	Mudbrick-MB	Adyton NW corner
K6A	Mudbrick-MB	Mid Geometric Temple, under Adyton
K12	Soil-S	Archaic Temple, Giebel area
K14	Soil-S	Slope between Temples
K8	Soil-S	Slope
K9	Earth filling -EF	Proto Geometric Temple Masonry
K1	Earth filling -EF	Archaic Temple NW corner of Sekos
K3	Earth filling -EF	Late Geometric Temple sub - foundation
N	Water-W	Water from Kalapodi Reservoir

Tab. 1 - Documented available materials in Kalapodi archaeological site for analysis (2017-2025). This paper focuses on the stone materials KL1-KL5

architectural elements from earlier structures were incorporated into later buildings, particularly after events like earthquakes or destruction. In addition, there are several mortars and wall paintings from the site (Table 1). The focus of this paper is on the stone material of the classical and archaic temples, namely samples with the code name KL1, KL2 and KL4. These stones are the most affected by frost phenomena and the weather conditions since the rest are currently covered by soil and therefore protected.

The porous limestone (code KL1), used in the construction of the classical temple in the northern complex, is pale yellow and primarily consists of calcite (91%), with grains of magnetite, quartz, and fossils. It has a bulk density of 2.21 g/cm³, a water absorption by mass of 15.23%, a total porosity of 31.06%, and a large average pore size of r Ø4.83 μm. Its mechanical strengths are 13.52 MPa in compression and 4.07 MPa in bending. In the construction of the archaic temple a limestone in ochre shade has been used, with two different qualities, found in different positions of the structure. The soft (code KL2) is found mainly in the sub-foundations and the harder (code KL4) in the upper structure. Both stones contain mainly calcite, magnetite granules (<2%) and fossils (~8%), are certainly local and come from the same rock sequence. The hard quality of the stone has a lower total porosity than the soft grade, 22-24% versus 26.8%, with a similar average pore size r Ø0.98-0.1 μm. The soft quality of limestone has a lower bulk density than hard quality (1.92 g/cm³ *vs*. 2.46 g/cm³) and twice the water absorption value by mass, 22.95% vs. 11.69% respectively (Kouzeli, 2001). The mechanical strength of the soft grade of limestone is lower, mainly in bending, with values of 6.25 MPa (compression) and 0.53 MPa (bending), compared to 8.17 MPa and 1.38 MPa for hard quality. All three types of limestone are certainly local and originate from the same rock sequence (Galanou *et alii*, 2017).

The temperature in Kalapodi can drop below 0o C for at least a week during winter, resulting in the formation of frost on the monument's building materials. The porosity of the materials is one of the main reasons for their disintegration since they absorb water, and the stresses developed due to the expansion of water within the pore network cannot be relieved. As a result, the stones gradually disintegrate (Fig. 12).

Fig. 12 - Phenomenon of erosion of soft limestone due to the effect of frost (DAI-Athen archive)

Similar phenomena are observed in the presence of certain salts, such as chlorides and sulfates, which also can expand when they are transformed from an anhydrous to an hydrated state. It would be expected that the insoluble salts would not affect the Kalapodi site, since its geographical position is in a distance from the sea (approx.15 km in straight line according to GoogleEarth). However, there are some indications of insoluble salts where salt efflorescence was detected in combination with weathering phenomena on the soft limestone blocks.

For these reasons, the three types of stone were tested under frost conditions (frost cycles) and were also subjected to artificial aging cycles with salts. Sample KL1 was selected from the porous stone of the classical temple, while for the archaic temple, samples KL2 for the soft limestone and KL4 for the hard limestone were chosen. Further to this study calcium hydroxide precipitation material in the form of nanoparticles (50-300 nm), commercially known as Nanorestore, was used as a consolidation material for the protection of stone. This material was applied on the samples and the coated samples were further tested for frost and aging cycles.

The results of the frost resistance tests indicated that the limestone of the classical temple is a durable material and does not appear to face significant issues. However, both types of stone from the archaic temple, the hard and the soft limestone, exhibited frost-related deterioration. Nonetheless, in the

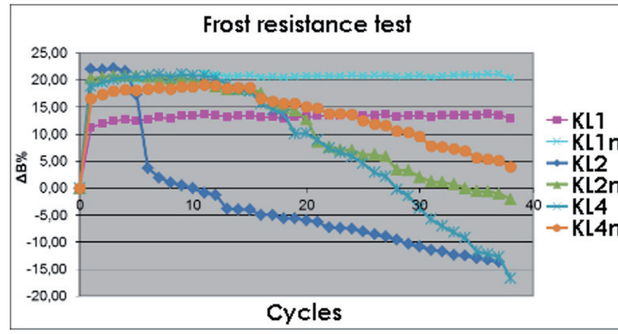

Fig. 13 - Frost resistance tests for the samples under study. The "n" refers to the coated stones with Nanorestore (Galanou et alii, 2017)

specimens treated with the consolidant material, the progression of erosion appeared to slow down (Fig.13).

In the artificial aging process, all samples demonstrated low resistance without exception, as deterioration became evident from the second cycle, with edge rounding and significant weight loss, while by the eleventh cycle, most specimens had been destroyed (Fig. 14). The application of the consolidant material did not seem to improve the resistance of the stones to soluble salts, except in the case of the porous stone used in the construction of the classical temple (samples KL1m and KL1n), where the consolidant material appeared to slightly enhance the material's performance.

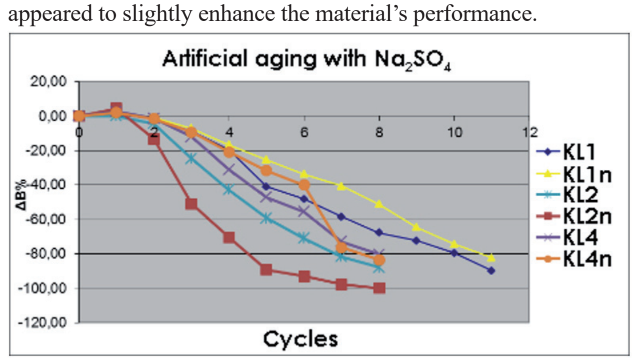

Fig. 14 - The results of the artificial aging process applied on Kalapodi building materials. The "n" refers to the coated stones with Nanorestore (Galanou et alii, 2017)

To further understand how climate change affects the archaeological site an exact replica of the steps and the stylobate of the Northern Temple with the application is in the process of being constructed with CNC (Computerized Numerical Control) in 1:1 scale with similar material to the original (Fig. 15). The material used is a limestone having similar properties to the original and in the near future as part of the Triquetra project will be used as a substrate for the application of coatings for the protection from frost as a case study. The acquired data will be then used to the ancient temple ensuring its preservation.

For the implementation of the replica preliminary earthworks took place to flatten the soil so as to construct a base/plate of

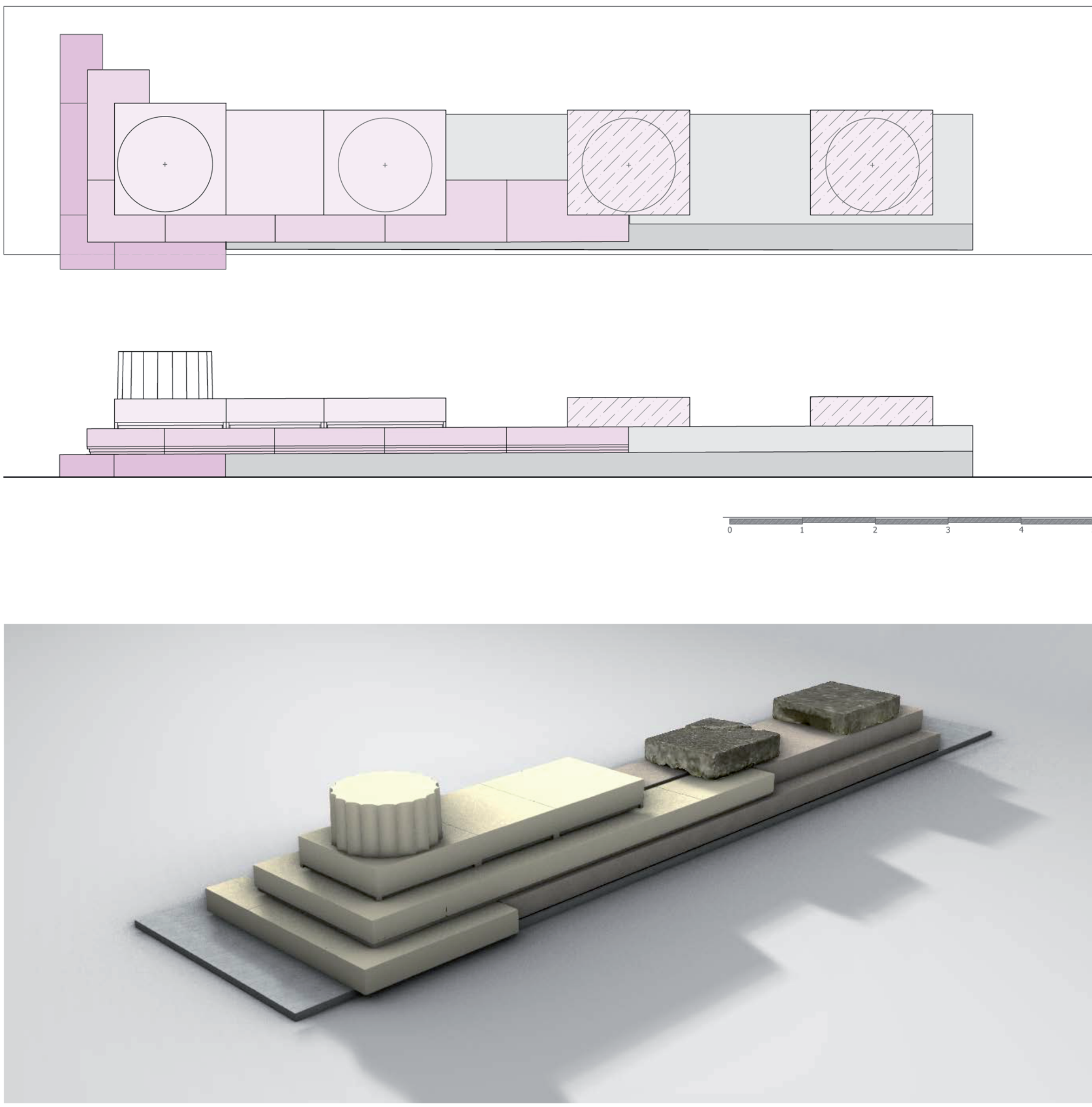

Fig. 15 - Implementation of TRIQUETRA programme at the site of Kalapodi. Drawing of the construction of a partial replica of the steps and stylobate of the Northern Tempel (Th. Bilis, DAI Athen) and a 3D model of the structure (P. Gourgouleti, DAI Athen)

lightly reinforced compatible mortar where the replica was built within the archaeological site at a location at a distance from the monuments. This infrastructure was also reinforced with the installation of underground power line which is of outmost importance to support the weather monitoring system (see below)

Weather data monitoring system was also placed next to the replica so as to collect meteorological data in a daily basis. The data are assessed to understand how temperature and humidity fluctuate across the site and weather there are many frost events during the short period of winter.

The protection of the materials against frost apart from the nano-coatings, which will be applied in the near future, will be also implemented with the installation of a mess with heated electrodes which will be activated when the temperature in the archaeological site approaches 3°C. Attached thermo-probes on the stone material of the replica will allow the recording of the on a daily basis and the behavior of the system during snowfall or/ and frost will be recorded by a thermal or/and visible light camera.

FINAL REMARKS

This research has shown the effects of weather conditions on the building materials of Kalapodi sanctuary in an effort to understand how climate change affects the stone material of the site. In this direction a risk assessment was possible through climate information for Kalapodi over the past period from 1971 to 2020. To this end, observational data from weather stations lying at the proximity of Kalapodi (E-OBS) and an ensemble of simulations (EURO-CORDEX RCM) were obtained and analyzed. According to the findings the observational data (E-OBS) show a characteristic increase in surface temperature during the examined 1970-2000 period at Kalapodi and when compared to the simulations satisfactory performance of the models is observed. Any discrepancies seen between the observed and modeled values are subject to model uncertainties and different topographical and morphological characteristics between the exact location of Kalapodi and the selected model nearest grid point.

Regarding frost the results from the Kalapodi site show that there is a strong connection between various climate variables and their impact on snow cover and subsequently frost. During the forthcoming decades a significant rise in temperature is sexpected which will affect/shift precipitation patterns, making the need for implementation strategies to safeguard cultural heritage and in particular Kalapodi site urgent. In addition, the implications of the findings of the current research underline the need for mitigation measures to encounter climate change as the reduction in snowfall could have subsequent effects such as change in the hydrology of the archaeological site which in turn can affect its preservation (Laghari *et alii*, 2012; Javadinejad *et alii*, 2020).

To moderate these risks, efforts at Kalapodi must focus on tailored conservation approaches. Drainage systems are essential to prevent water gathering, which exacerbates frost damage and erosion. Such actions have already been applied so far in the landscaping projects at Kalapodi site. Seasonal protection measures, such as temporary coverings, can shield vulnerable structures during periods of extreme frost or heat. Long-term monitoring is also crucial. Installing localized weather stations to collect data on temperature, humidity, and precipitation would enable more precise modeling of climatic impacts and allow conservation strategies to adapt dynamically. In addition, application of novel materials using nanotechnology will allow the protection of the monuments with custom made coatings and the application of digital technologies, such as Digital Twin (already applied in Kalapodi from the Aristotle University of Thessaloniki - TRIQUETRA partner), allows future assessment of the preservation status of the monument.

Understanding and addressing the region's climatic conditions is critical to preserving the archaeological and historical significance of Kalapodi in the face of these environmental challenges. These findings emphasize the vulnerability of cultural heritage to the impacts of climate change, underscoring the critical need for additional research on future climatic conditions.

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