"DIAGNOSTIC STUDY AT THE ACROPOLIS OF SARANTAPICHO AND THE ACROPOLIS OF ERIMOKASTRO, RHODES"

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ABSTRACT

This work presents the use of non-destructive techniques as testing tools for the diagnostic study of structural materials. Their contribution is essential for the successful design of necessary conservation interventions on monuments, which in this case are the Acropoles of Sarantapicho and Erimokastro at Rhodes, Greece. The diagnostic study of the masonry's structural materials was carried out using the Non-Destructive Technique of Ground Penetrating Radar, supported by an array of instrumental characterization techniques which included polarized optical microscopy, X-ray diffraction, scanning electron microscopy, mercury porosimetry, conductivity measurements and mechanical testing to characterize the structural materials and their decay products. Results revealed the extensive biodecay present on the two types of stones, grey compact limestone and off-white limestone, that results in cracking, delamination and detachment of original material.

1. INTRODUCTION

The Acropolis of Ialyssos (Sarantapicho) site is located at the northeastern part of Rhodes island and take it's name from a legend that the Acropolis was guarded by a giant 40 "piches" high, whereas his alleged tomb is an almost equally long water supply tunnel that is present nearby. There are indications that the Acropolis was protected by cyclopean walls of the Mycenaean period and few remains are evident throughout the site. Unfortunately, the majority of the surviving structure of the Acropolis of Ialyssos is in a state of decline due to the use of the limestones from the ancient walls as raw material for a nearby cement industry.

On the other hand, the Acropolis of Erimokastro (Deserted Castle) is an established archaeological site, also located at the northeastern part of the island of Rhodes at a natural hill between Kallithea and Afantou bays. It's walls are multifaceted and possibly of cyclopean type, 2-4m high and 1,7 – 2m wide, built from rubble stones [1]. The walls at Erimokastro are in a better state, probably due to the location of the site which did not allow easy removal of building material.

Both sites were selected to perform a diagnostic study that will form the basis of their restoration and protection [2]. As part of the diagnostic study, the materials and their decay state were characterized using an array of non-destructive techniques validated and supported by a series of instrumental methods. The instrumental techniques are used to assess the mineralogical and chemical composition, the microstructure and the mechanical properties of the materials examined and aid in the understanding of the prevailing decay phenomena. The combined use of instrumental and non-destructive techniques can lead to the mapping of the structural materials, the assessment of the environmental impact on them, the diagnosis of their decay, that support an integrated design of the proposed conservation interventions [4]. This information can be utilized by geographical information systems [5] that can present the current decay status of the monuments and correlate it with architectural data.

2. EXPERIMENTAL

In this study, Ground Penetrating Radar (GSSI SIR-2000 with a 1500MHz antenna) was used to investigate a water supply tunnel at Sarantapicho and reveal subsurface cracks at building stones in both sites. This was supported by an array of instrumental characterization techniques which included polarized optical microscopy (OM), X-ray Diffraction (XRD), Scanning Electron Microscopy combined with Energy Dispersive X-ray (SEM-EDX), Mercury Porosimetry (POR), conductivity measurements and mechanical testing.

3. RESULTS & DISCUSSION

3.1. Macroscopic investigations

The first part of a diagnostic study gives an introductory insight on the materials present at these monuments and their current state of decay. The macroscopic observations at Sarantapicho reveal that the abundant grey limestone has developed cracks, cavities and detachments (Fig. 1). Extensive presence of biodecay is observed mainly in the form of grey-white lichens, whereas the cavities between the building blogs are filled with earth. In some areas of the walls significant plant growth is observed.

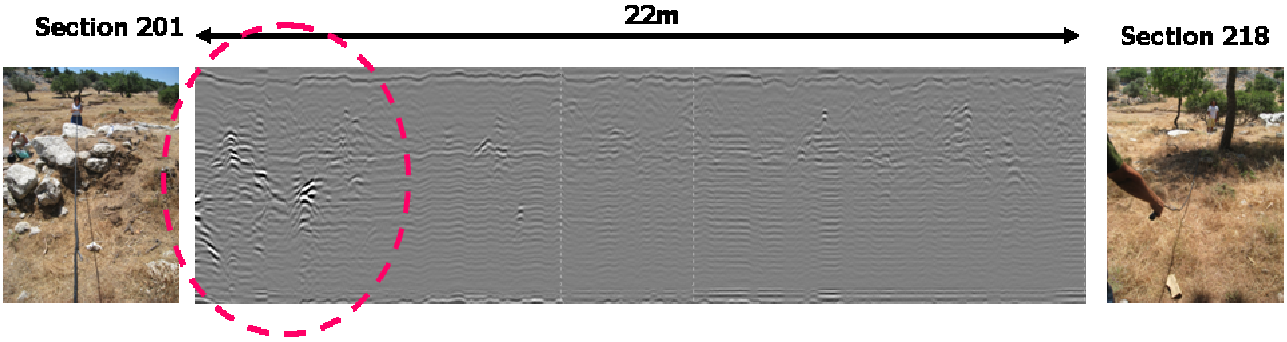
Fig. 1. Sarantapicho: a. Biodecay; b. Cavities' formations; c. Cracks on grey limestone

At the Erimokastro Acropolis, grey dolomite with dark-brown inclusions is present with off-white fossiliferous limestone (Fig. 2). Extensive biodecay is observed with white, black and orange colored lichens. In general, the stones present cracks, detachments and delaminations whereas the dark-brown inclusions contain many surfacial cracks; the off-white stones in particular, reveal alveolar decay. The dry-stone wall presents large cavities between the building blocks which in some cases are filled with smaller filler stones. Although the site is an established archaeological monument, plants and trees are not taken care off and have been allowed to grow even close to the wall foundations.

Fig. 2. Erimokastro: a. Grey limestone with dark-brown inclusions; b. Off-white stone

3.2 Ground Penetrating Radar

The systematic scanning with ground penetrating radar over an ancient water supply tunnel at Ialyssos Acropolis, revealed that the tunnel is open up to approximately 3meters from its entrance, whereas the remaining portion of it, has either collapsed or filled with earth (Fig. 3). GPR was also employed to detect internal cracks, discontinuities and surface defects at selected stones at both sites. Fig. 4 shows GPR scans on a grey limestone at the entrance of the Ialyssos, where it was revealed that a surfacial crack at the side of the stone extends at the interior in a planar mode, almost down to the center of the stone. Similar results were obtained from Erimokastro samples, that corresponded satisfactorily with results from other non-destructive techniques employed.



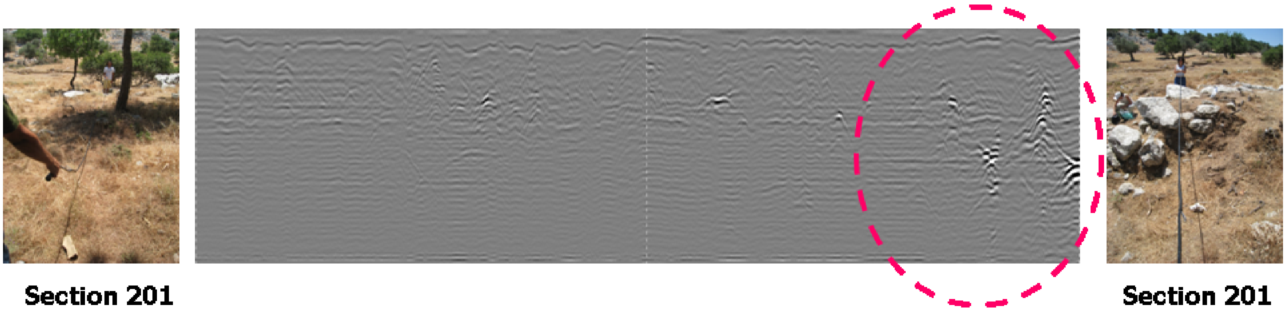


Fig. 3. Longitudinal scanning with ground penetrating radar over the water supply tunnel at Ialyssos Acropolis

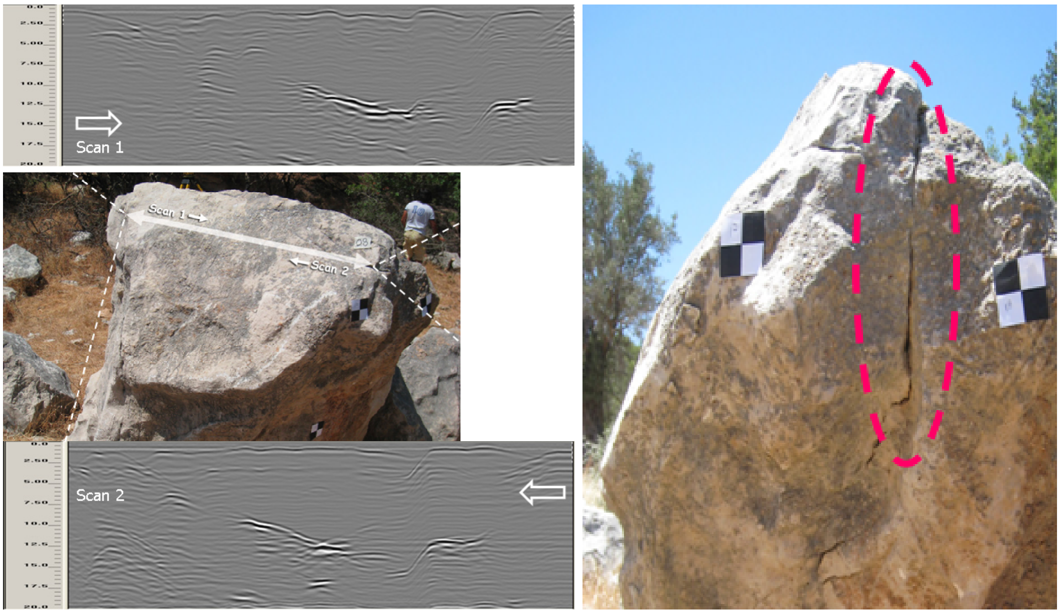


Fig. 4. Sarantapicho: GPR scans on a grey limestone show that the surfacial crack extends down to the center of the stone, in a planar mode.

3.3 Petrographic Analysis

The petrographic analysis was performed with polarizing microscopy and X-ray Diffraction. It was revealed that at Erimokastro (Fig. 5) the grey colored stone is limestone, whereas the off-white stones are limestone with presence of fossils. The dark-brown inclusions are chert. At Sarantapicho, (Fig. 6) the grey stone is fossiliferous limestone.

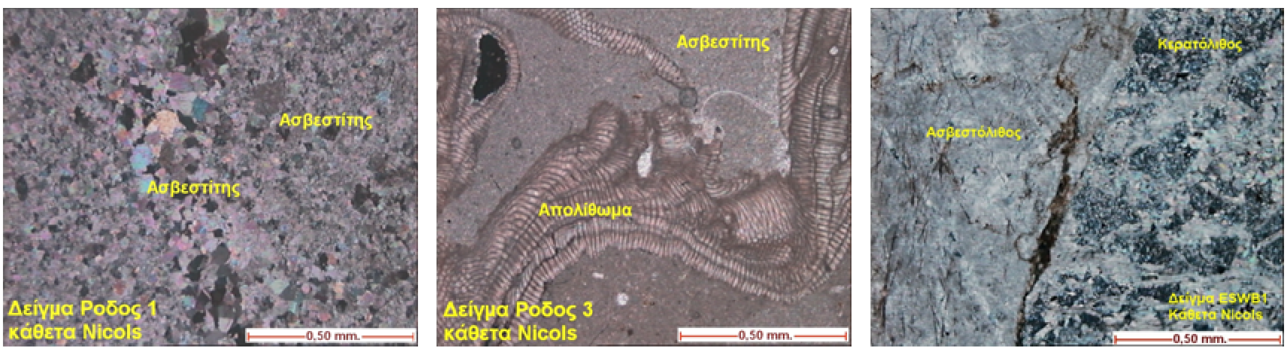


Fig. 5. Polarizing microscopy of stone samples at Erimokastro. Left: Grey limestone. Middle: off-white fossiliferous limestone. Right: Dark-brown inclusion.

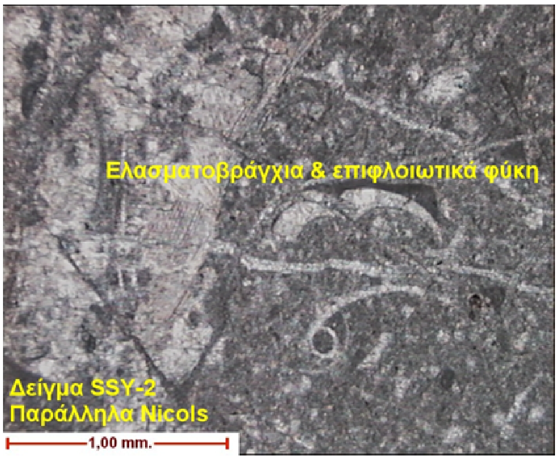


Fig. 6. Polarizing microscopy of the fossiliferous limestone samples at Sarantapicho

3.4 Mechanical properties

Compression tests of stone samples from Sarantapicho revealed that the compression strength varied from 32.2 to 181.4 MPa with an average value of 112 MPa. According to literature the compression strength of limestones, breccia and travertines varies between 63 and 88 MPa, whereas marbles and compact limestones between 88 and 147 MPa. The variance of the examined stone samples is indeed higher than that of the literature values, however the average value falls within those of the compact limestones, thus it is assumed to be representative of the samples.

3.5 Microstructural analysis

Mercury porosimetry reveals that at Sarantapicho the abundant grey limestone presents low porosity (~1%), and in particular high percentage of small pores (Table 1). The variations are due to different sampling points at the surface of the stones (not the interior). At Erimokastro (Table 2), the porosity of the grey limestone is approximately 1% with high percentage of small pores. The occasional dark-brown inclusions (possibly of siliceous composition) have an even smaller porosity (0.3 – 0.5%), whereas the off-white fossiliferous limestone presents much higher porosity ~6-6.5% mostly of large pores which is detrimental for the absorption of soluble salts.

Table 1. Microstructural analysis of stone samples from Sarantapicho

Sample ID	**Total Specific Volume** (mm^3/g)	**Apparent Density** (g/cm^3)	**Total Porosity** (%)	**Average Pore Radius** (μm)	**Specific Surface** (m^2/g)
SES8-1	2.47	2.69	0.66	2.76	0.03
SES8-1(2)	10.94	2.63	2.87	18.38	0.39
SES8-2	1.74	2.71	0.47	0.02	0.19
SESr1	1.14	2.70	0.3	0.63	0.02
SESr1(2)	0.32	2.73	0.8	4.17	0
SSr2	0.73	2.70	0.19	0.02	0.07

Table 2. Microstructural analysis of stone samples from Erimokastro

Sample ID	Total Specific Volume (mm³/g)	Apparent Density (g/cm³)	Total Porosity (%)	Average Pore Radius (μm)	Specific Surface (m²/g)
Grey Limestone					
EWSg1	3.72	2.68	0.99	0.33	0.04
RHERS1	2.08	2.69	0.55	0.01	0.2
RHERS1(2)	3.91	2.68	1.05	0.01	0.74
Dark-brown inclusion					
EWSb1	2.05	2.62	0.53	0.01	0.2
EWSb1(2)	1.83	2.59	0.47	0.03	0.13
EWSb2	0.17	2.63	0.04	3.35	0
EWSb2(2)	1.16	2.61	0.3	1.62	0
Off-white fossiliferous limestone					
EWSw1	24.76	2.53	6.26	13.27	0.87
EWSw1(2)	37.43	2.43	9.09	26.52	1.07
RHERS2	10	2.54	2.54	0.01	0.8
RHERS2(2)	29.37	2.44	7.16	0.01	2.8
RHERS3	26.88	2.47	6.63	0.34	0.26
RHERS3(2)	28.15	2.48	6.98	8.24	0.41

The microscopic observation with scanning electron microscopy reveals the extent and origins of the biological decay, in particular an extensive development of fungi. In particular, at Sarantapicho the pitting at the surface is attributed to biodecay (Fig. 7). Of particular notice is the development of carpic structures that enhance the growth of lichens and the development of texture that is indicative of early stages of micelle growth. Dust particles are also present that consist of pollen grains attached to the bonding material of the biolayer at the surface of the grey compact limestone.

At Erimokastro, the grey compact shows similar micelle formation textures at the stones. The off-white fossiliferous limestone shows pitting and micelle formation, as well as presence of NaCl salt crystals, whereas the dark-brown inclusions reveal how the surfacial growth of micelles penetrate vertically at the main body of the stones leading to surfacial cracks (Fig. 8)

3.9 Total soluble salts content

Table 3 presents the results from the determination of the total soluble salt content of the stones examined. At Sarantapicho, the percentage of the soluble salts range between 2.52 – 2.72%, values that are characterized as low. It could be, however, attributed to the low porosity of the stone and to the fact that the site is at an elevated altitude on the mountains,. At Erimokastro, however, which is located right next to the sea, similar values are observed for the grey compact limestone and slightly higher values for the off-white fossiliferous limestone which has almost 6 times higher porosity than the grey one.

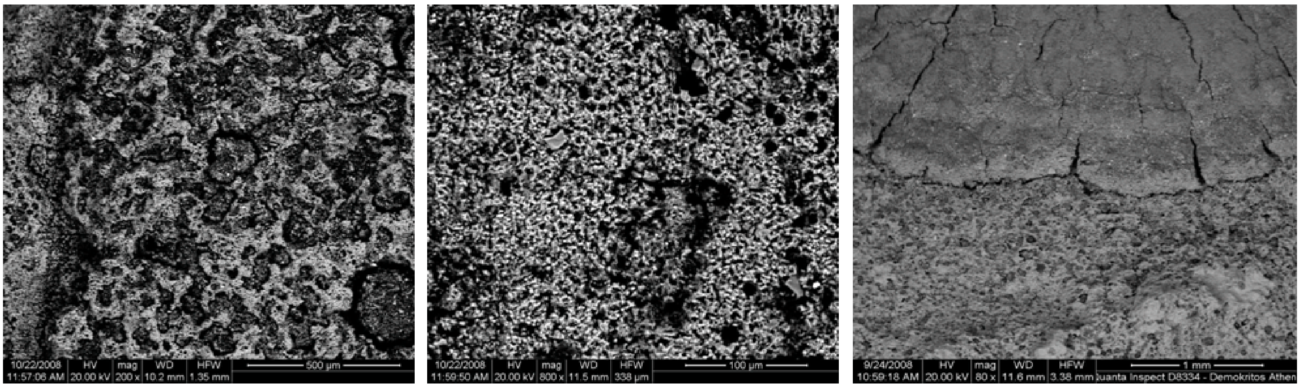


Fig. 7. Scanning electron micrographs of stone samples at Sarantapicho.
Left and middle: Typical pitting due to biodecay at the surface of the stone and development of carpic structures. Right: Interface of lichens – stone where cracks are observed at the lichen surface

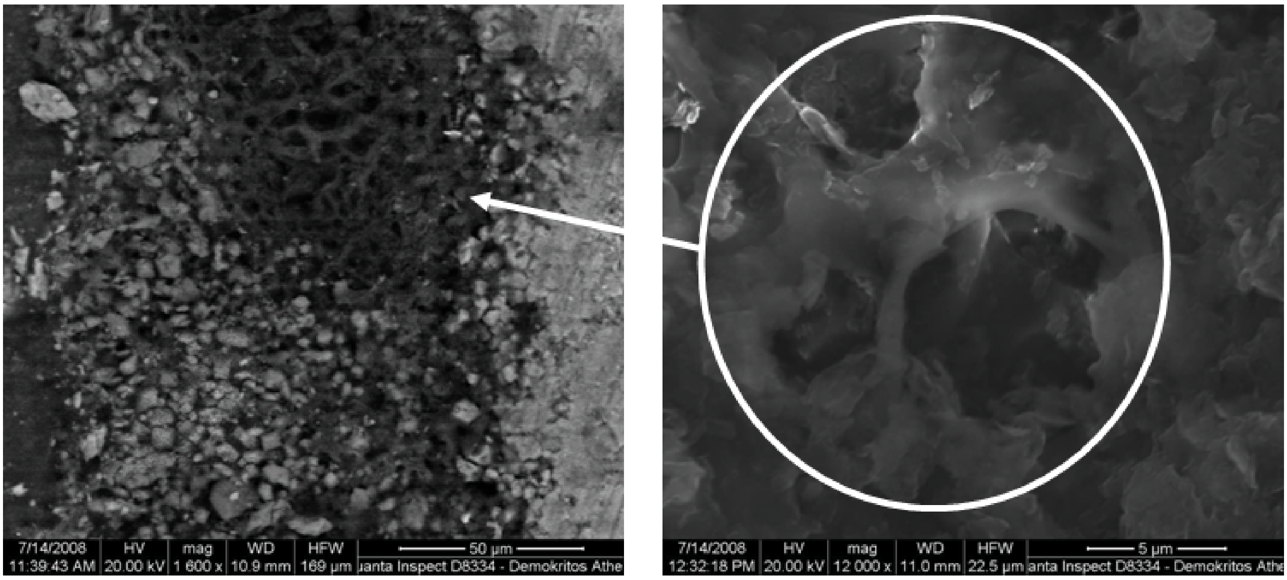


Fig. 8. Scanning electron micrographs of stone samples at Erimokastro.
Grey compact limestone with typical pitting due to biodecay– thickness of the lichen is ~100µm.

Table 3. Total soluble salts content

Sample	A (μS)	% SST	Cl-
Sarantapicho			
SES8-1	47.8	2.72	+
SES8-2	47.6	2.69	+
SESr1	47.2	2.52	++
SSr2	47.3	2.68	+
Erimokastro			
Off-white fossiliferous limestone			
EWSw1	55	3.18	+
ECS3	56.8	3.31	+
Grey compact limestone			
EWSg1	47.7	2.70	++
Dark-brown inclusion			
EWSb2	46.7	2.65	+
EWSb1	46.2	2.53	++

4. CONCLUSIONS

With the exception of the off-white fossiliferous limestone (6%) at Erimokastro, the other building materials examined presented a low porosity, below 1%. In all type of building stones extensive biodecay products of grey-white or orange color that is attributed to lichen formation and cracks and detachment of stone material were observed. The biodecay is attributed to the extensive fungi growth that results in coloring of the stone (dark greyblack), pitting and microcracking, and to the conglomerates of dust particles consisting of pollen grains. The dark brown inclusions present intense surfacial cracks, pitting due to biodecay and extensive fungi micelle growth that penetrate vertically towards the main body of the stone. Moreover, the off-white fossiliferous limestone presents alveolar decay due to salt crystallization at the interior of the stone [8].

Concluding, the use of non-destructive techniques in conjunction with instrumental characterization methods, allowed the successful assessment of the decay status and the mapping of the decay phenomena on the structural stones of the walls of the Acropolis at Ialyssos, and the Acropolis at Erimokastro (Fig. 9 and Fig. 10)

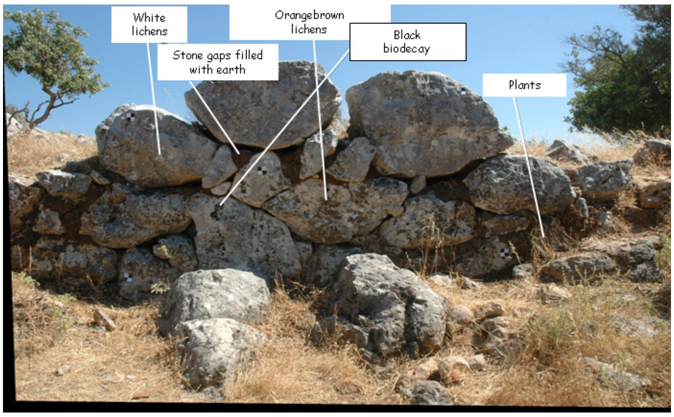


Fig. 9. Decay phenomena at Erimokastro

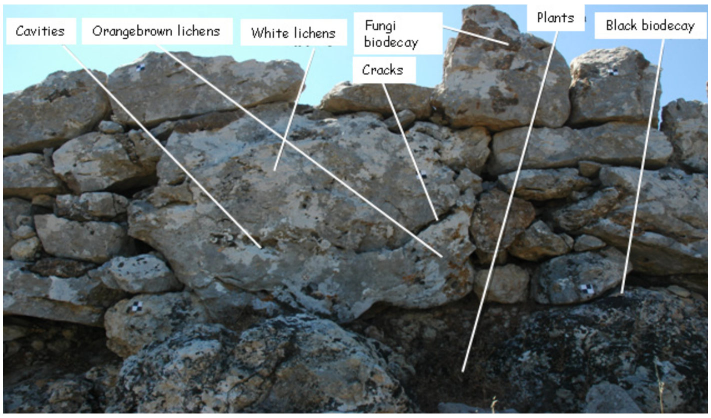


Fig. 10. Decay phenomena at Erimokastro

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