Final Scientific Report

KoEF Research Cooperation Project

Project Overview

Project Title	Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia). Building research and conservation studies for the development of future preservation and presentation strategies		
Acronym	-		
Project Number	KOEF 02/2020		
Cooperating Countries	Austria, Tunisia		
Coordinating Institution	Austrian Academy of Sciences, Austrian Archaeological Institute (OeAW-OeAI)		
Project Coordinator	Dr. Gudrun Styhler-Aydın		
Email Coordinator	gudrun.styhler-aydin@oeaw.ac.at		
Partner Institution 1	Institut National du Patrimoine / National Heritage Institute (INP)		
Project Co-Coordinator	Hamden Ben Romdhane		
Email Co-Coordinator	hamden042001@yahoo.fr		
Please insert lines for further partners.			
No. of All Involved Institutions			
Austrian Institutions	1) Austrian Academy of Sciences, Austrian Archaeological Institute (OeAW-OeAI)		
Partner Country Institutions	2) Institut National du Patrimoine / National Heritage Institute (INP)		
Project Start	01.09.2021		
Duration in Months	12 + extension		
Total Costs Applied (€)	20.000€		
No. of Team Members (including Coordinator)	Male: 1	Female: 5	Total: 6
Coordinating Institution (including Project Coordinator)	Male:	Female: 3	Total: 3
Partner Institution 1 (including Co-Coordinator)	Male: 1	Female: 2	Total: 3
Please insert lines for further partners.			
Branch(es) of Science[1] (max. 3)	Cultural heritage	605008	
	Building research	201205	
	Conservation, restoration	604018	

[1] http://www.statistik.at/kdb/downloads/pdf/OEFOS2012_EN_CTI_20190903_162012.pdf

Contribution to SDGs[2] (max. 3)	Sustainable cities and communities; in particular 11.4: Strengthen efforts to protect and safeguard the world's cultural and natural heritage	11; in particular 11.4
	Quality education	4
	Decent work and economic growth; especially 8.9: By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	8; especially 8.9

[2] https://sustainabledevelopment.un.org/sdgs

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Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia).

Building research and conservation studies for the development of future preservation and presentation strategies

KOEF 02/2020

A collaboration project of

Austrian Archaeological Institute at the Austrian Academy of Sciences, Austria

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Österreichisches Archäologisches Institut

and

l'Institut National du Patrimoine (Tunisie) / The National Heritage Institute, Tunisia

المعهد الوطني للتراث
Institut National du Patrimoine
National Heritage Institute

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1. Abstract / Zusammenfassung

The ancient hydraulic complex of Zaghouan in present-day Tunisia was built from the 2nd century to the beginning of the 3rd century and is one of the most impressive testimonies to Roman hydraulic engineering. From several springs on Mount Zaghouan (Djebel Zaghouan) the water was fed into the pipeline and transported to Carthage within a pipeline system over a length of about 132 km. In 2012, the entire Zaghouan – Carthage hydraulic complex, which significantly shapes the archaeological landscape in the rural area between Tunis and the source areas, was included in the Tentative List of UNESCO World Heritage Sites. Since then, efforts have been underway to create the conditions for inscribing this important ancient building and infrastructure ensemble on the UNESCO World Heritage List. This is the point at which the project started by expanding research on selected elements of the Zaghouan – Carthage hydraulic complex with targeted scientific studies, thus providing new bases for the historical classification as well as the preservation of the ancient structures.

The Zaghouan – Carthage hydraulic complex has not yet been fully explored scientifically. Although explorers have described and documented parts of the hydraulic complex since the 19th century, important sections of the water pipeline have still not been documented and scientifically analyzed by building research. Questions about the precise chronological classification of individual buildings and sections of the pipeline are also still open. The same applies to the cistern installations. In order to provide further bases for the overall understanding of the hydraulic complex, the conducted research focused on a part of the spring sanctuary in Zaghouan and two sections of the aqueduct, one at Oued Miliane and one beside the large Malga cistern plus a general examination of the Malga cistern structure itself. Within this frame, three important construction and utilization phases of the hydraulic complex were mainly addressed: Antiquity and Late Antiquity (2nd-7th century), Middle Ages (12th century) and Modern Times (with emphasis on the 19th century).

The project aimed to develop important scientific basics for the exploration and preservation of the ensemble within the framework of a research cooperation between the Austrian Archaeological Institute at the Austrian Academy of Sciences (OeAW-OeAI) and the Tunisian National Heritage Institute (INP). With targeted scientific investigations, the existing research on selected elements of the entire complex was continued and an expanded knowledge base for the historical classification of the ancient structures has been created. The results will significantly support the process of inscribing the Roman Hydraulic Complex Zaghouan – Carthage in the UNESCO World Heritage List by providing sound scientific and conservation documentation and analyses based on current methods. The results also serve to develop strategies for the preservation and future presentation of this extraordinary historical building ensemble.

With its focus, the project contributed to several sustainable development goals of the United Nations. Goal 11.4 "Strengthen efforts to protect and safeguard the world's cultural and natural heritage" was addressed centrally.

The project involved young female scientists in particular, whose cooperation and scientific exchange further expanded the existing partnership and international cooperation between the Austrian Archaeological Institute (OeAW-OeAI) and the Tunisian National Heritage Institute (INP).

Der antike Hydraulikkomplex von Zaghouan im heutigen Tunesien wurde zwischen dem 2. und dem Beginn des 3. Jahrhunderts erbaut und ist eines der eindrucksvollsten Zeugnisse römischer Wasserbautechnik. Aus mehreren Quellen auf dem Berg Zaghouan (Djebel Zaghouan) wurde das Wasser in die Rohrleitung eingespeist und über ein Aquäduktsystem von etwa 132 km Länge nach Karthago transportiert. Im Jahr 2012 wurde der gesamte Hydraulikkomplex Zaghouan – Karthago, der die archäologische Landschaft im ländlichen Raum zwischen Tunis und den Quellgebieten maßgeblich prägt, in die Vorschlagsliste des UNESCO-Welterbes aufgenommen. Seitdem wird daran gearbeitet, die Voraussetzungen für die Aufnahme dieser bedeutenden antiken Bau- und Infrastrukturensemble in die UNESCO-Welterbeliste zu schaffen. An diesem Punkt setzte das Projekt an, indem es die Erforschung ausgewählter Elemente des Wasserkomplexes Zaghouan – Karthago durch gezielte wissenschaftliche Studien erweiterte und damit neue Grundlagen für die historische Einordnung sowie die Erhaltung des antiken Bauensembles schafft.

Der Hydraulikkomplex Zaghouan – Karthago ist wissenschaftlich noch nicht vollständig erforscht. Obwohl Forscher seit dem 19. Jahrhundert Teile des Ensembles beschrieben und dokumentiert haben, sind wichtige Abschnitte der Wasserleitung noch immer nicht durch die Bauforschung dokumentiert und wissenschaftlich analysiert worden. Auch die Frage nach der genauen zeitlichen Einordnung einzelner Gebäude und Leitungsabschnitte ist noch offen. Das Gleiche gilt für die Zisternenanlagen. Um weitere Grundlagen für das Gesamtverständnis des hydraulischen Komplexes zu schaffen, konzentrierten sich die durchgeführten Untersuchungen auf einen Teil des Quellheiligtums in Zaghouan und zwei Abschnitte des Aquädukts, einen am Oued Miliane und einen neben der großen Zisterne in Malga, sowie eine allgemeine Untersuchung der Zisternenanlage La Malga selbst. Innerhalb dieses Rahmens wurden vor allem drei wichtige Bau- und Nutzungsphasen des Hydraulikkomplexes behandelt: Antike und Spätantike (2.-7. Jahrhundert), Mittelalter (12. Jahrhundert) und Neuzeit (mit Schwerpunkt auf dem 19. Jahrhundert).

Das Projekt hatte zum Ziel, im Rahmen einer Forschungskooperation zwischen dem Österreichischen Archäologischen Institut an der Österreichischen Akademie der Wissenschaften (ÖAW-ÖAI) und dem tunesischen National Heritage Institute (INP) wichtige wissenschaftliche Grundlagen für die Erforschung und Erhaltung des Ensembles zu erarbeiten. Mit gezielten wissenschaftlichen Untersuchungen wurde die bestehende Forschung zu ausgewählten Elementen der Gesamtanlage fortgesetzt und eine erweiterte Wissensbasis für die historische Einordnung der antiken Bauwerke geschaffen. Die Ergebnisse werden den Prozess der Aufnahme des Hydraulikkomplexes Zaghouan – Karthago in die UNESCO-Welterbeliste durch eine fundierte wissenschaftliche und konservatorische Dokumentation und Analyse auf der Basis aktueller Methoden maßgeblich unterstützen. Die Ergebnisse dienen auch dazu, Strategien für den Erhalt und die zukünftige Präsentation dieses außergewöhnlichen historischen Gebäudeensembles zu entwickeln.

Mit seiner Ausrichtung trug das Projekt zu mehreren nachhaltigen Entwicklungszielen der Vereinten Nationen bei. Das Ziel 11.4 "Verstärkte Anstrengungen zum Schutz und zur Bewahrung des Kultur- und Naturerbes der Welt" wurde zentral angesprochen.

Das Projekt bezog vor allem junge Wissenschaftlerinnen ein, deren Mitarbeit und wissenschaftlicher Austausch die bestehende Partnerschaft und internationale Zusammenarbeit zwischen dem Österreichischen Archäologischen Institut (ÖAW-ÖAI) und dem tunesischen National Heritage Institute (INP) weiter vertiefte.

2. Introduction, objectives and overview of the project

2.1 Introduction

The ancient hydraulic complex of Zaghouan in present-day Tunisia was built from the 2nd century to the beginning of the 3rd century and is one of the most impressive testimonies to Roman hydraulic engineering. From several springs on Mount Zaghouan (Djebel Zaghouan) the water was fed into the pipeline and transported to Carthage over a length of about 132 km. Subsequently, a second spring in the Jouggar region was also connected to the pipeline. The Zaghouan – Carthage hydraulic complex included, in addition to the structures for the pipeline (at ground level as well as elevated on arcades), several nymphaeums or spring sanctuaries in Zaghouan and Jouggar as well as the cistern of Bordj Djedid. (Fig. 1-5) Another large cistern, the cistern of Malga (Fig. 6) was in close neighborhood of the pipeline. Starting from the cisterns, the water was distributed within Carthage. Famous supply points in the city were the Antoninus Pius Baths, which required a constant water supply. From late antiquity onwards, sections of the aqueduct were destroyed and rebuilt for several times. Beginning in the 16th century, it also served as a quarry. Nevertheless, in the second half of the 19th century, the water supply system was successfully renewed by following the ancient structures. Since its re-commissioning in 1862, it still supplies areas of Tunis with water.

In 2012, the entire Zaghouan – Carthage hydraulic complex, which significantly shapes the archaeological landscape in the rural area between Tunis and the headwaters, was included in the Tentative List of UNESCO World Heritage Sites.[3] Since then, efforts have been underway to create the conditions for inscribing this important ancient building and infrastructure ensemble on the UNESCO World Heritage List.

This is the point at which the present project starts by expanding research on selected elements of the Zaghouan – Carthage hydraulic complex with targeted scientific studies, thus providing new bases for the historical classification as well as the preservation of the ancient structures.

Fig. 1: The Roman spring sanctuary of the aqueduct in Zaghouan with the mountain massif in the background (G. Styhler-Aydın, OeAW-OeAI 2019)

Fig. 2: A section of the Roman aqueduct structure in the Miliane Valley (G. Styhler-Aydın, OeAW-OeAI 2021)

[3] http://whc.unesco.org/en/tentativelists/5685/ (last access: 02.04.2024).

Fig. 3: The revitalized aqueduct structure of the 19th century after the Miliane Valley (G. Styhler-Aydın, OeAW-OeAI 2021)

Fig. 4: A section of the aqueduct structure at the level of the Bardo in today's Tunis (G. Styhler-Aydın, OeAW-OeAI 2022)

2.2 State of Research

The Zaghouan – Carthage hydraulic complex has not yet been fully explored scientifically. Although explorers have described and documented parts of the hydraulic complex since the 19th century, a complete analysis is still a desideratum. However, comprehensive research and documentation work on individual elements of the complex already exists. Herewith especially the nymphaeums and spring sanctuaries are addressed. The large spring sanctuary in Zaghouan and sections of the water pipe were investigated by F. Rakob from the German Archaeological Institute (DAI) in the 1960s and 1970s. During recent archaeological research, a small nymphaeum and another elliptical monument (1998 by N. Ferchiou / INP) were uncovered near the source sanctuary. Remarkable here is, among other things, that a section of the (later) water pipe covers this monument. The nymphaeum of Jouggar, which was integrated secondarily into a Byzantine fortification, has been the subject of a research project by INP with the German Archaeological Institute in Rome since 2018 (project management H. Ben Romdhane/INP and R. Bockmann/DAI Rome).

Investigations into the technical parameters of the water pipeline have also been conducted and published, especially by P. Caillat 1873 in the frame of the re-commissioning of the water supply system. 1998-2001, in the frame of an international study at the Universidade Nova de Lisboa[4] focused on the degradation phenomena in ancient and traditional building materials, investigations on individual sections of the water pipeline were carried out to determine structural aspects, the building materials used (including material analyses), and the construction and restoration techniques. In the same initiative, a cooperation between the Universitat Autònoma de Barcelona and the University of Tunisia did petrophysical characterizations especially of the sandstone used for the structure of the aquaeduct.

Due to its size and complexity, the Roman hydraulic complex Zaghouan – Carthage including all its related structures, historical extensions, intentional historical damages and repairs is still not completely scientifically investigated.

[4] EURO-MED, INCO-DC Concerted Action IC18-CT-0384, financially supported by the European Union (DG XII-CEOR). Compare: https://sites.fct.unl.pt/culturalmaterials/pages/degradation-historical-building-materials (last access 02.04.2024).

Fig. 5: A section of the aqueduct structure in the area of the Malga cistern in Carthage (G. Styhler-Aydın, OeAW-OeAI

Fig. 6: View on ancient water tanks of the Malga cistern in Carthage (G. Styhler-Aydın, OeAW-OeAI 2022)

2.3 Objectives and Overview of the Project

The project aimed to develop important basic knowledge for the exploration and preservation of the hydraulic complex Zaghouan – Carthage within the framework of a research cooperation between the Austrian Archaeological Institute (OeAW-OeAI) and the Tunisian National Heritage Institute (INP). Specifically, a part of the spring sanctuary in Zaghouan and two sections of the aqueduct, one at Oued Miliane and one beside the large Malga cistern, were investigated followed by a general examination of the Malga cistern structure itself. The project focused on three important construction and utilization phases of the hydraulic complex: Antiquity and Late Antiquity (2nd-7th century), Middle Ages (12th century) and Modern Times (with emphasis on the 19th century).

The project was planned for 12 month and divided into 4 work packages. Two field research stays in Tunisia (WP 1, WP 3) were dedicated to the building documentation and conservation-scientific inventory of the selected sections of the aqueduct and the Malga cisterns. It also included archive research in Tunis on historical written information, pictures and plan material of the aquaeduct structure. A research training in Vienna trained the Tunisian team members how to use further postprocessing procedures for the finalization of an integrative building analysis (WP3). In the last phase of the project, all partial results were brought together and discussed in a colloquium. Preparation work on the publication of project results started. (WP 4). After work package 3, the project coordinator decided to expand the conservation-scientific inventory by mortar analyses which were conducted by Dr. Farkas Pintér of the University of Applied Arts Vienna and financed by the research group *Historische Bauforschung* of OeAW-OeAI, where the project was conducted.

Due to several changes of the working and travel conditions during the Covid-19 pandemic, the former planned schedule of the project had to be adapted, but could be conducted successfully in the following work packages:

WP 1 Documentation and analysis of a selected building part of the spring sanctuary in Zaghouan and a section of the aqueduct structure at Oued Miliane.

WP 2 Documentation and analysis of an aqueduct section at the cistern of Malga; general examination of the cistern structure itself. Archive research in the INP archive in Tunis.

WP 3 Finalization of the resulting plans and mappings of the building survey. Training on postprocessing procedures at OeAI Vienna for the Tunisian colleagues using the documented material and survey data of WP 1-2.

WP 4 Final workshop and preparation of topics/content for publication.

3. Narrative summary of the project: activities and results, elaboration of the research findings, methodology used, innovative aspects of the project

3.1 Research stays for the project

The following 3 research stays were implemented according to the project proposal:

1) Fall 2021 field campaign in Tunisia from Oct. 17 – Nov. 07, 2021

Tasks: WP 1: Documentation and analysis of a selected building part of the spring sanctuary in Zaghouan and a section of the aqueduct structure at Oued Miliane

Outcome: - Digital 3D laser scan documentation of the temple cella including adjacent structures of the porticus
- Conservation-scientific inventory of the temple cella (mapping condition and damages, non-destructive testing)
- Digital 3D laser scan documentation of an about 80m long section of the aqueduct structure at Oued Miliane; plan record, analysis of construction and mappings (material mappings, phases of construction, catalogue of features)
- Conservation-scientific inventory of the temple cella (mapping condition and damages, non-destructive testing)

2) Spring 2022 field campaign in Tunisia from March 06 – 27, 2022

Tasks: WP 2: Documentation and analysis of sections of the aqueduct structure at the cisterns of Malga and general examination of the cistern structure itself. Archive research in the INP archive in Tunis.

Outcome: - Digital 3D laser scan documentation of 3 sections of the aqueduct and cistern structure; plan record and analysis of construction and building phases
- Conservation-scientific inventory of 3 sections of the aqueduct and cistern structure; (mapping condition and damages, non-destructive testing, sampling)
- Comparison with the structure of the aqueduct in the Bardo area (Tunis)
- Study of historical documents on the aqueduct structure and maintenance in the INP archive in Tunis

3) Summer 2022 stay at OeAI Vienna from June 01/15 – 30, 2022

Tasks: WP 3: Finalization of the resulting plans and mappings of the building survey. Training on postprocessing procedures at OeAI Vienna for the Tunisian colleagues using the documented material and survey data of WP 1-2.

WP 4 Final workshop and preparation of topics for publication

Outcome: - Final plans and mappings of the building surveys of field campaigns in Tunisia
- Summary of the information gained from archive documents regarding the

aqueduct structure
- Workshop at June 21st, 2022: Presentation and discussion of all results of the building survey and analysis, the conservation-scientific inventory including the mortar sampling analysis and the archive research
- Table of contents for paper publication in English / French
- Practice in postprocessing procedures with focus on 3D laser scan data

3.2 List of all research stays

Activity	Location	Date	Particitpants
Fall 2021 field campaign	Zaghouan and Provinz Zaghouan, Tunisia	17.10.–07.11.2021	K. Dridi, K. Mighri, B. Rankl
		17.10.–03.11.2021	I. Mayer
		17.–24.10.2021	G. Styhler-Aydın
Spring 2022 field campaign	Carthage / Tunis, Tunisia	06.–27.03.2022	K. Dridi, I. Mayer, K. Mighri, B. Rankl
		06.–13.03.2022	G. Styhler-Aydın
Summer 2022 stay at OeAI	Vienna, Austria	01.–30.06.2022	K. Dridi, K. Mighri
		15.–30.06.2022	H. Ben Romdhane

3.3 Reports of all research stays of project members

See Annex A:

1_ Reports of Khaoula Dridi, MA (INP)
2_ Reports of Dipl.-Ing. Irmengard Mayer (OeAW-OeAI)
3_ Reports of Khaoula Mighri, MA (INP)
4_ Reports of Mag. art. Barbara Rankl (OeAW-OeAI)
5_ Report of Dr. Hamden Ben Romdhane (INP)
6_ Reports of Dipl.-Ing. Dr. Gudrun Styhler-Aydın (OeAW-OeAI)

3.4 Methodology used

For the exemplary investigation of selected sections of the Roman hydraulic complex between Zaghouan and Carthage, the methods of integrated building documentation and construction analysis were combined with conservation-scientific inventory. In addition, comparative studies were carried out on other sections of the aqueduct (nymphaeum in Jouggar, aqueduct on the Bardo in Tunis) as well as research into historical pictures and reports in the INP archive in Tunis.

A terrestrial 3D laser scanner Faro Focus 3D 120S was used for the on-site building survey. The scanner's target points were measured tachymetrically with a Leica TS07 total station. Based on the 3-dimensional recording of the building structures with the laser scanner, architectural sections (vertical, horizontal) and orthogonal projections of the wall views were generated from the registered point cloud, which served as the basis for further analysis and reporting. Since no higher-level coordinates were available, all measurements of the individual survey areas were recorded in local coordinate systems, set on basis of a tachymetric polygon tracks. For areas that were not accessible for the scanner, a

photogrammetric recording was done with a Sony ILCE-7MR3 camera, 50mm lense.
After completion of the post-processing and the elaboration phase, the results are plan sets (floor plan, views, sections), mappings (e.g., construction phases, material used, individual findings), catalogs (masonry catalog, findings catalog) and a structured written description for each section examined. A photo documentation completed the building survey.

The conservation-scientific inventory and condition survey as basis for the development of a preservation concept focused on the following topics, which were integrated to the topics of building research:

- Investigation of the materials of all construction phases (stones, mortarts, etc.), documentation of the production techniques and traces of processing
- Documentation of previous restoration measures
- Damage recording and analyzing the main causes of damage, as well as evaluation of the state of preservation

Only non-destructive examination methods were used on site, such as HCL tests, Karsten test tubes, Schmidt hammer, salt tests, etc. The assessment also included an optical evaluation of the condition, a detailed description of the condition with forms, graphic documentation through mapping and a photo documentation of the relevant findings.

In addition to the conservation-scientific inventory within the project, a petrographic analysis of mortar samples from the aqueduct structures in Oued Miliane and Malga was organized and financed by the OeAW-OeAI and permitted by the INP. A number of 8 Roman and Medieval mortar samples were taken on site and brought to the University of Applied Arts Vienna. Dr. Farkas Pintér, Institute of Conservation, conducted the investigation with the aim to characterize and compare the mortars originating from the mentioned sampling sites.

3.5 Research findings

For detailed results of the building survey and the conservation-scientific inventory and condition survey see the reports of I. Mayer and B. Rankl in Annex A. The many results of such investigations are not repeated here again.

3.5.1 Spring Sanctuary in Zaghoan

The spring sanctuary in Zaghouan (Fig. 1) as the beginning of the water pipeline to Carthage became particularly well known through descriptions by European travelers of the 19th century, such as Philippe Caillat[5]. In the mid-1960s, Friedrich Rakob of the German Archaeological Institute surveyed and analyzed the remaining building stock and published his findings, including a comprehensive set of plans and photographic documentation, in a publication that remains fundamental to this day[6]. Since then, this building documentation has been and continues to be referred to in various scientific studies as well as in travel literature. Additional building archaeological investigations of the spring sanctuary and the surrounding area were carried out in 1998 by archaeologist Naide Ferchiou from the INP[7].
Building on this state of research, an accurate-to-shape survey based on 3D laser scanning was first carried out 2021 in the present project (see report by I. Mayer 2021). The focus was on

[5] Caillat 1873.
[6] Rakob 1974.
[7] Ferchiou 2018; Ferchiou 2009; Ferchiou – Khosrof 2002, 21; Ferchiou 1999.

the state of preservation of the cella with the adjacent vaulted bays of the portico. In a second step, the current survey formed the basis for the mapping of the findings with regard to the building material used (from the construction period and from restoration phases in the 1980s/1990s) as well as damage due to ageing and decay (see report B. Rankl 2021, p. 5-10). The most common types of damage can be attributed to two causes. Firstly, this is the natural weathering of the gray limestone of the cella walls, which has been exposed to climatic conditions for centuries without a final architectural finish or maintenance measures. The second cause of damage is related to the tourist use of the area, which has led to wear and tear (and unfortunately also partial defacement) of the ancient surfaces. Visitor guidance that respects sensitive areas of the monument, the development of a monitoring concept (also to assess and monitor structural safety) and the regular implementation of maintenance measures are recommended here.

3.5.2 Aqueduct in the Miliane Valley

Starting from the spring at Djebel Zaghouan, the water was carried to Carthage over a distance of more than 90km in a pipeline that ran above and below ground (Fig. 2, 3). The end point of the pipeline was initially a large water reservoir in the hill of Bordj Djedid, through which the large Antonine baths could be continuously supplied with water. Since its construction in the 2nd century, the water pipeline between Zaghouan and Carthage has had a very varied history, which has already been described in detail by F. Rakob and N. Ferchiou[8], among others. Since the turn of the millennium, material studies on the historical construction materials and deposits in the pipeline channel from the period of use have come to the foreground[9].

With the aim of a conservation-scientific investigation and description, an aqueduct section of approx. 80m in length in the Miliane Valley was selected for documentation and analysis in the current project. In addition to the ancient construction phase, medieval additions, historical consolidations and repairs as well as modern restorations are also visible here. The selected section with a preserved height of the construction up to approx. 11.50m is characterized by 11 vaulted bays between 12 pillars.

In view of the enormous length of the water pipeline between Zaghouan and Carthage, which was routed over long stretches on (single and multi-storey) arcades in accordance with the gradient of the pipeline in low-lying plains such as the Miliane Valley, the existing building documentation available in the research literature understandably shows exemplary sections of the aqueduct to illustrate its architecture, construction and dimensions. Longer sections of the pipeline were only shown schematically. However, a detailed survey was required for the tasks set in the current project. This is probably the first time that a longer aqueduct section has been accurately surveyed using 3D laser scanning, photogrammetry and tachymetry (see I. Mayer 2021 report).

The three-dimensional data set generated subsequently formed the basis for the recording of building materials, construction techniques and damage to be observed (see report B. Rankl 2021, pp. 11-16). As a result of the conservation-scientific inventory and analysis, the causes of damage are mainly due to signs of decay of the building material. Particularly noticeable were statically unstable areas and the extensive loss of the architectural surface in the examined section. The loss of substance can only be countered with a carefully planned

[8] See Ferchiou – Khosrof 2002; Ferchiou 1999; Rakob 1974.

[9] Figueiredo – Veiga – Silva 2001; Figueiredo et al. 2000.

conservation concept. In view of the various, locally limited restoration measures carried out in the recent past, each with its own appearance, an overarching restoration objective with coordinated structural conservation measures for the entire aqueduct section in the Miliane Valley is proposed here.

3.5.3 Aqueduct and Cisterns in Malga/Carthage

In the Malga area, the water pipeline reaches the outskirts of Carthage from the north (Fig. 5). Here there are several cisterns, a monumental ancient hydraulic complex and sections of pipelines from different periods. The large cistern of Malga (Fig. 6), which was built on an area of 131 x 102m, is widely known. The cistern complex is structured into 15 longitudinal compartments, which are covered by barrel vaults. In the apex of the barrel vaults, round openings are placed at regular intervals. The 15 cisterns, built parallel to each other, are preconnected in a later construction phase by a narrow transverse cistern. All sections of the facility are connected to each other. The water level inside is assumed to be about 4 m. The capacity is estimated at more than 44.000m^3. The Malga cisterns have been part of the UNESCO World Heritage Site Carthage since 1979[10].

The water pipe here runs along the south-eastern façade of the existing cistern and then continues in a south-westerly direction. In the recent past, Habib Baklouti devoted himself to this area in extensive archaeological research[11]. As a result of excavations by Simon P. Ellis 1996, the branch of the aqueduct to supply the Antonine Baths is located around 300m north-east of the large cistern[12]. For the current project, it was of interest to compare the construction of the aqueduct and the cross-section of the specus with the measurements from the Miliane valley and to obtain further details on secondary structural changes to the pipeline in the area of the large cistern. 3D laser scanning, tachymetry and photogrammetry were used to create a partial survey in 3 areas, on the basis of which further documentation and building analysis was carried out (see report by I. Mayer 2022). The conservation survey was also carried out in these areas and supplemented the structural information with valuable knowledge about the condition and state of preservation of the historic building materials (see report B. Rankl 2022).

In summary, the most frequent damage patterns in this section of the aqueduct can be attributed to natural weathering processes, particularly of the main building materials lime-sandstone and sandstone, which in turn promote damage caused by biological colonization. However, the state of preservation is not homogeneous. Some areas of the aqueduct have only recently been restored. In other areas, consolidation of the severely weakened masonry structure is still outstanding.

Another stress factor is the visitor traffic in this area, which is often used for leisure activities, which also leaves its mark on the ancient monument.

3.6 Innovative aspects of the project

The project was innovative in several respects. The interdisciplinary composition of the team from the fields of historical building research, archaeology, restoration and architecture

[10] https://whc.unesco.org/en/list/37 (last access 02.04.2024).

[11] Baklouti 2003; Baklouti 2008; Baklouti 2015; Baklouti 2017; Baklouti 2018; Baklouti 2019a; Baklouti 2019b.

[12] Ellis 1996.

enabled a comprehensive view of the selected areas of investigation of the Roman hydraulic complex between Zaghouan and Carthage. Particularly noteworthy here is the close interlinking of the building survey and conservation-scientific inventory on site, through which, among other things, a deeper understanding of the ageing processes of the building structures could be achieved, including the classification of historical consolidation, repair and restoration work. This enabled a holistic view of the ancient monument and at the same time provides a sound basis for future strategies for its preservation and tourist presentation. It can be said that the selected survey sections were measured and documented for the first time using modern building recording technology. The digital data generated will be available for further analysis beyond the scope of the project. The building documentation and analysis at various scales (from the aqueduct section to the masonry detail) also revealed other topics that had not previously been considered in research on the monument, such as the care and structural maintenance measures on the ancient supply infrastructure[13] or the changes to the building structures, including the reuse of reclaimed building material, for which a wide range of evidence was found. Last but not least, the combination of older research results with information from the archive material and current findings enables a new view of the monument, which also includes the constant historical processes of change and the conditions of its use.

In view of the sheer size of the Roman Hydraulic Complex, however, the project with its innovative aspects can only be an impetus and starting point for further analysis.

4. Contribution to the SDGs and implementation of gender and diversity issues

The project activities contributed to several Sustainable Development Goals (SDGs) of the United Nations:

Goal 11 was addressed centrally: „Make cities and human settlements inclusive, safe, resilient and sustainable", in particular **11.4**: "Strengthen efforts to protect and safeguard the world's cultural and natural heritage". Here, the project results provide further basics for the maintenance and preservation of aqueduct sections and related building structures. Furthermore, the support of the gained knowledge for the process to inscribe the Roman hydraulic ensemble into the UNESCO World Heritage List – the INP is highly involved here – has to be mentioned.

Through the transfer of knowledge during the site research and the integrated training for young Tunisian scientists, the project also contributed to **Goal 4**: "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all".

Furthermore, the project results supported **Goal 8**: „Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all", and especially **8.9**: „By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products". In terms of the Zaghouan – Carthage hydraulic complex, the INP pursues the strategy to promote and to communicate this cultural heritage, e.g., in the frame of thematic exhibitions and the plans for a "water museum".

[13] Also compare Sürmelihindi et al. 2023.

In the collaborative project conducted, ethical and gender-related concerns were recognized and integrated within the framework of responsible and equitable research practices.

5. Sustainability and application of results

5.1 Sustainability of the project and application of results

Within the research project, the objectives focused on the scientific contribution to the exploration and preservation of the Roman hydraulic complex Zaghouan – Carthage by investigating selected parts of the structure.

In view of the size of the structural remains, it was clear from the outset that the project would initially only be able to work on an exemplary basis. The planned focus on selected sections of the aqueduct and associated buildings, such as the spring sanctuary in Zaghouan, made it possible to develop and effectively implement an integrated workflow on site, from building documentation and analysis to conservation assessment. In addition to the substantive results, this successfully applied approach is now available for further research into the hydraulic complex. By extending the existing state of research, the results of the applied project created a new basis for:

a) the scientific classification of the Roman hydraulic complex Zaghouan – Carthage and

b) the development of strategies for the preservation and future use of this extraordinary historical building ensemble. Especially the project results of the condition survey can contribute to maintenance measures and preventive maintenance of the complex historic structures.

However, the project's impact goes far beyond the scientific contribution. First of all, the support of the process to inscribe this outstanding ancient hydraulic ensemble on the UNESCO World Heritage List should be mentioned here. Future conservation measures connected with this process will increase the attention for the cultural heritage and can be a starting point for the further development of attractive offers of sustainable tourism in the rural areas concerned.

At the local level, the project's activities to research and preserve cultural heritage in Tunisia raised awareness of issues related to building research and monument preservation. As a result, other people involved in promoting cultural heritage in Zaghouan became aware of the project activities and invited the Austrian-Tunisian team to visit an exhibition on the city's historical water supply dating back to the 19th century, for example.

The close cooperation between the Austrian and Tunisian team members enabled early career researchers in particular to gain international professional experience that will be valuable for their own future projects. In technical-methodological terms, the project offered Tunisian colleagues in-depth knowledge in the field of integrated high-tech building survey and analysis. The Austrian team members benefited from the cooperation by discussing different approaches of research and long-term preservation of architectural ensembles of this unusual size and by exchanging corresponding experience.

5.2 Status of partners and partner organisations, scope for follow up projects and activities

The collaboration project of the Austrian Archaeological Institute (OeAI) at the Austrian Academy of Sciences (OeAW) and the National Heritage Institute (INP) of Tunisia was coordinated by Dipl.-Ing. Dr. Gudrun Styhler-Aydın, head of the research group *Building Research and Cultural Heritage* at the OeAI, and co-coordinated by Dr. Hamden Ben Romdhane, researcher in History and Archaeology of Ancient Civilizations at the INP. The conducted project was the third collaboration of the partners and contributed to further deepen their international scientific cooperation.

The ***Austrian Archaeological Institute (OeAI) at the Austrian Academy of Sciences (OeAW)*** is a research institute. Its core competence is basic archaeological research in field archaeology and all its subfields. The tasks also include cultural and historical analyses based on the material remains as well as preservation measures.[14] The institute is dedicated to interdisciplinary, transnational and teamwork-based research following international scientific standards.

On OeAW-OeAI side, the project was conducted at the research group *Building Research and Cultural Heritage*. In addition, the expertise and equipment of the OeAI departments of *Geodesy* and *Restoration* were available to the project. Based on projects to study the Roman water supply of the city of Ephesus in Asia Minor (Turkey) for many years, the OeAW-OeAI also provided field experience regarding the analysis of Roman aqueducts and a knowledge collection on Hydraulic Engineering in the Mediterranean.[15]

The ***National Heritage Institute (INP)*** is a public administrative institution under the Tunisian Ministry of Culture. As a scientific and technical institution, it is responsible for establishing the inventory of Cultural Heritage in Tunisia in terms of archaeological, historical, civilizational and artistic aspects. The institution is doing research for the analysis, preservation and restoration of Cultural Heritage. Furthermore, the INP participates in the development of heritage and its promotion nationally and internationally.[16]

In terms of the Zaghouan – Carthage hydraulic complex, the INP is highly involved into the nomination process as UNESCO World Heritage Site.

With the completion of the project, the digital building documentation of the Roman Hydraulic Complex Zaghouan – Carthage is now available to become part of the virtual exhibition in the planned local museum in Zaghouan (responsible for exhibition: H. Ben Romdhane) and will thus reach national and international visitor groups. The project results are in the working process of scientific publication and will be available for the use on Tunisian visitor information platforms or tourist information apps.

Follow-up projects – e.g., in the frame of the Cooperation Development Research calls of OeAD – are of high interest and were already discussed among the partners. One aim is the extension of the applied investigations to further sections of the Roman hydraulic complex Zaghouan – Carthage, which due to its size and complexity is still not completely geodetically recorded and scientifically investigated.

[14] https://www.oeaw.ac.at/en/oeai/institute/mission-statement (last access 02.04.2024).
[15] Compare Wiplinger 2019; Wiplinger 2016; Wiplinger 2006.
[16] https://inp.rnrt.tn/en/inp_tunisie/ (last access 02.04.2024).

6. Partnership and cooperation within the project

The project participants – the early career researchers are explicitly addressed here – expanded their experience in the relevant project areas by close cooperation. The knowledge gained in the project can be independently applied in future scientific collaborations. With regard to future research cooperation in the fields of archaeology, building research and cultural heritage, the further expansion of these capacities is of great interest to both partner institutions.

6.1 Reflection on the project environment

The project represented a deepening of the already existing but still young cooperation between OeAW-OeAI and INP and was supported with commitment on both sides during implementation. This was evident, for example, in the preparation of the field research, which required a number of permits (e.g., for the import of high-tech surveying equipment such as 3D laser scanner or working in archaeological protection zones and on listed buildings) from the Tunisian authorities, all of which were obtained in good time by the co-coordinator. During the documentation and analysis work on the aqueduct and related structures, the project team was supported by the organization of workers to clean selected areas and the provision of simple equipment and transport facilities by the INP.

As the project partners are a scientific institute or an administrative-scientific institute and have extensive project experience, appropriate workstations were available for the preparation and evaluation of the data collected during the field research. For example, the co-coordinator's office in the archaeological museum in Carthage was used during the spring 2022 campaign. Workstations in offices were also provided for the Tunisian partners' stay at the OeAI in Vienna in June 2022.

Last but not least, the committed and independent handling of tasks by the early career researchers in the team, who were also responsible in their day-to-day work outside the project (as curator for the World Heritage Site of the Medina of Tunis, architect at the INP, academic restorer or scientific project assistant at the OeAI), enabled the project to run smoothly.

6.2 Response to challenges and difficulties, unexpected outcomes

The biggest challenge in the project was dealing with the effects of the Covid-19 pandemic. On the one hand, this concerned planning uncertainties with regard to national and international travel, which could be countered by restructuring the work packages in the project. On the other hand, the effects of the pandemic also changed the working reality of both partner institutions. The resumption of international project activities on all sides following the lockdowns and travel restrictions led to a high demand within the institutes for the use of the institute's own equipment and generally to a high level of staff involvement in order to implement projects that had been canceled or to make up for project visits. In addition, a resurgence of international conference activities and postponed scholarship stays filled the institutes' calendars.

All of this had an impact on the partners' work program and the originally intended project

schedule. For example, the planned one-month technical training course for the Tunisian early career researchers at the OeAW-OeAI in Vienna had to be shortened considerably, as the technical specialists at the OeAI were heavily involved into the resumption of international excavation activities. The planned discussion of the preliminary project results with international experts in Roman hydraulic engineering technology also had to be postponed for the time being due to a lack of time options. These restrictions were accepted in favour of additional time for the evaluation of the unexpectedly rich archive research and the further elaboration of the project results in the form of plan drawings.

7. Reflection on project success with special regard to project aims and expected results

With regard to the data collection as part of the building documentation and construction analysis as well as the on-site conservation and scientific findings, all project objectives were achieved despite the restrictions imposed by the effects of the Covid-19 pandemic (WP 1 and 3 of the application). An extensive data set from the construction documentation and analysis as well as the conservation assessment is available for the exemplary analyzed sections of the aqueduct and related structures. This includes plan drawings, mapping, chemical analyses and textual descriptions. The findings on the building structures were supplemented by historical descriptions in the INP archive. So far, however, only brief reports have been published. The final evaluation and publication of the material has not yet been completed. Two publications in scientific series are planned (see Chapter 8).

The training on geodetic methods for data acquisition of built heritage and discussion of stone conservation topics in Austria (WP 2 of the application; see Chapter 6.2) could only be implemented to a limited extent. As this development was already apparent during the course of the project, the Austrian team endeavored to introduce their Tunisian colleagues to the methodology as much as possible during the field research. The intended training was also made more difficult by the technical failure of the INP's 3D laser scanner, meaning that it was only possible to work with the OeAI's 3D laser scanner on site.

The exchange with the international specialist community (WP 4 of the application) was also delayed due to the pandemic and is currently being expanded. The planned international online colloquium is therefore still a goal that is to be realized (even outside the time frame of the project).

8. Publications

Published project actitvity reports:

Österreichisches Archäologisches Institut, Jahresbericht / Austrian Archaeological Institute, Annual Report 2022; Wien 2023, pp. 103-105; DOI: 10.1553/oeai.report2022
https://www.oeaw.ac.at/fileadmin/Institute/OEAI/PDF/Aktuelles/20230919_OeAI_JB_2022_e-book.pdf

Österreichisches Archäologisches Institut, Jahresbericht / Austrian Archaeological Institute, Annual Report 2021; Wien 2022, pp. 99-102; DOI: 10.1553/oeai.report2021
https://www.oeaw.ac.at/fileadmin/Institute/OEAI/PDF/Kommunikation/Jahresberichte/OeAI_JB_2021__e_book.pdf

Planned paper publications by all project members:

G. Styhler-Aydin, H. Ben Romdhane, K. Dridi, I. Mayer, K. Mighri, B. Rankl: *Investigating the Roman hydraulic complex between Zaghouan and Carthage. Building research and conservation studies for the development of future preservation and presentation strategies* (preliminary title)

G. Styhler-Aydin, H. Ben Romdhane, K. Dridi, I. Mayer, K. Mighri, B. Rankl: *The Roman Hydraulic complex between Zaghouan and Carthage. Historic restoration and maintenance measures reflected by archive reports* (preliminary title)

9. Pictures

See also Annex B for plan material.

Fig. 7a, b: 3D laser scanning of the aqueduct in the Miliane valley (I. Mayer, OeaW-OeAI Wien 2021)

Fig. 8a, b: During the building survey and conservation-scientific investigation in the spring sanctuary in Zaghouan (G. Styhler-Aydın, OeaW-OeAI Wien 2021)

Fig. 9: Cella of the spring sanctuary in Zaghouan during the investigation (G. Styhler-Aydın, OeaW-OeAI Wien 2021)

Fig. 10: Building survey of the aqueduct structure in Malga/Carthage (G. Styhler-Aydın, OeaW-OeAI Wien 2022)

Fig. 11a, b: Conservation-scientific inventory and condition survey in Malga/Carthage. Left: Cistern structure. Right: Specus of the aqueduct (G. Styhler-Aydın, OeaW-OeAI Wien 2022)

Fig. 12a, b: The structural remains of the so called Hafside Aqueduct at Bardo/Tunis (G. Styhler-Aydın, OeaW-OeAI Wien 2022)

Fig. 13a-c: Area of Malga/Carthage. Secondary built aqueduct structures (left, middle). Reused material from the ancient aqueduct for pipeline pillars of a later construction phase (G. Styhler-Aydın, OeaW-OeAI Wien 2022)

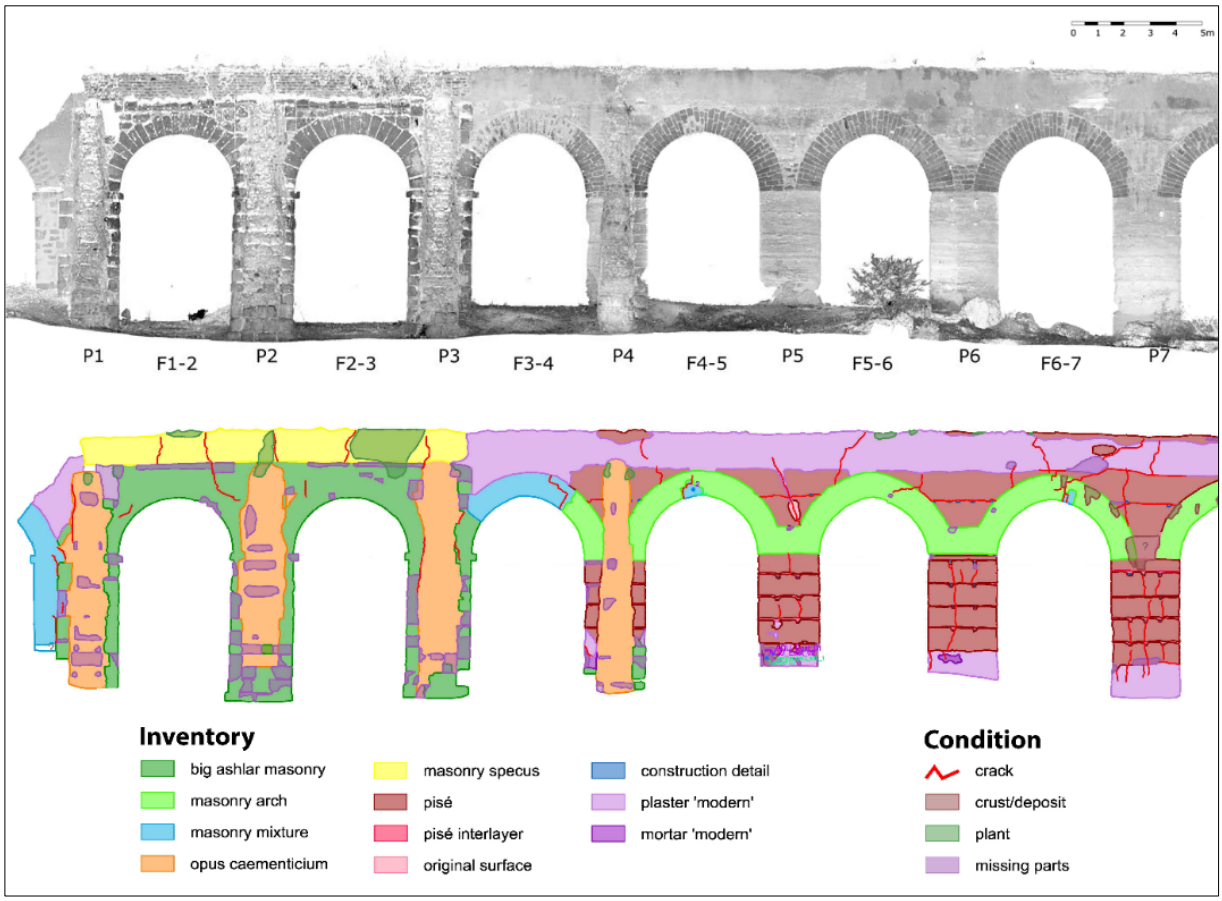

Fig. 14: Illustration of the workflow. Top: 3D laser scanning of the structure and generation of orthoprojections in scale. Below: Conservation-scientific inventory and condition mapping (I. Mayer – B. Rankl – K. Mighri – K. Dridi, OeAW-OeAI & INP 2021-2022)

	Wall 01-Restoration	Wall 02-Restoration	Variation of wall 02	Wall 03- Roman Arch	Wall 04- Roman "robbed"	Wall 05-Restoration
Material-Stone	sand stone	sand stone		sand stone	Residues of sand stone	Sand stone
Material-Mortar	Soft mortar / subrounded aggregats	hard / dense; colour pinkish to orange aggregates: different type of minerals mainly silicate		hard , white, aggregates: different mineral components similar to opus caementicium but with finer aggregates	White, porous; Opus caementicium with different stones (lime and sandstone); Orange patina	Aggregats Pinkish to white dense "white cement " hard
Biggest aggregates grain dimension	about 5 mm	about 4 mm		up to 4 mm	4 cm, rounded (mainly) grain till angular / different mineral components	4 mm different sand minerals, mainly silicate
Smallest visible aggregates grain dimension	below 1 mm	1 mm		1 mm	1 mm	Below 1 mm
The binding media	beige to brown	probabely hydraulic mortar; some lime lamps visible		average porosity, probabely hydraulic lime mortar	White "hydraulic lime" lime lamps up to 1 cm	White to pinkish, Very dense, hydraulic binding media
Tool Marks	Stone: Pointed chisel	Stone: Pointed chisel in different sizes ; joints: mortar surface smoothed, "Fugenstrich", wire brush		Stone: Pointed chisel; Joint: One joint preserved with flatten / smoothed surface	Imprints of big blocks	Mortar tool : brushes / wire brush Stone tool : pointed chisel
Joint dimensions	Horizontal joint : 2, 3,1.5, 3.5, 2.5, 1.5,1,1.5 Vertical joint : 4.5,1,2.5,5			Joint in the wall : between 6 mm to 10 mm 2 cm, 1.7, 1.5, 1	-	Horizontal joint vertical distance : 4.5,4.5, 3.5, 3, 2.5, 3.5 Vertical joint horizontal distance : 4.5, 3, 4.5, 6.5
Joint condition	Damaged joint morter Some of vertical joint are left open/ In between two stones is not filled	shrinking cracks, black biofilm (little) lichens		Damaged and missing joints sometimes	-	good condition
Stone Dimensions	Heights= 21, 20, 27, 26, 18, 19, 19, 30, 18, 17 Widht = 48, 42, 32, 35, 31, 29, 30, 28, 30	Horizontal distance between vertical lines : 69, 48, 51.5, 50, 48.5, 46, 56 Vertical distance between horizontal : 26, 25, 26, 27.5, 26.5		Vaulting stone : wedge like stone h1 : 12.5, 11, 11.5, 10.5, 14, 11.5, 9.5, 8.5 h2: 15, 15.5, 16,19, 15, 15, 12.5; "keilförmiger Anlaufstein" H 30 bis 42 cm ; Stones in "Zwickel" H 16, 16.5, 14, 11.5,17.5	Height : 43, 56,50 Width: 131, 77, 43, 43 (just imprints)	Height : 22, 22.5, 23.5, 22, 26.5, 19, 19.5 Width : 24, 30, 23, 8, 26
Stone Condition	sanding, scaling, erosion, microbiology : linches, black biofilm	Sanding, black biofilm, lichens		Sanding, scaling, erosion , black biofilm , scratches (anthropogenic mechanical damages)	Good condition no major damages	good condition; no major damages; one vertical crack

Fig. 15: Exemplary section of the wall catalogue with a systematic description of the masonry found (B. Rankl – K. Mighri – K. Dridi, OeAW-OeAI & INP 2021)

10. Further Comments

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