Annex A: Reports of all project stays of project members

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)

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OeAD KOEF Project
“Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia).”

STAY Reports

- **Report on October/November 2021 stay in Zaghouan, Tunisia**
- **Report on June 2022 stay in Vienna, Austria**

Khaoula Dridi
June 2022

Austrian Archaeological Institute
المعهد الوطني للتراث
INSTITUT NATIONAL DU PATRIMOINE

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I. Summary of the research project

The project *"Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia). Building research and conservation studies for the development of future preservation and presentation strategies"* was conducted as a cooperation between the Austrian Archaeological Institute at the Austrian Academy of Sciences (OeAI-OeAW) and the National Heritage Institute of Tunisia (INP) under the coordination of Dr. Gudrun Styhler-Aydin and the co-coordination of Dr. Hamden Ben Romdhane. It was funded by the OeAD in the frame of the Cooperation Development Research Call 2020.

During the field research, our study focused on the construction methods and techniques, the building materials used as well as the history of the restoration work that the aqueduct between Zaghouan and Carthage including related structures have undergone. The main objective during the field research stays was to conduct an in-depth study of three parts of the aqueduct chosen by the Tunisian–Austrian team.

Firstly, the on-site study made it possible to inventory the various structural elements of the aqueduct (inventory of the construction system) as well as the state of conservation (production of plans and mappings).

Secondly, based on the architectural field study on the one hand and bibliographical data on the other hand, the historical development of the selected parts of the monument including phases of consolidation and repair could be described.

Following the building material identification (large block stone or medium-sized stone, rubble, coating, rammed earth, etc.), the more recent restorations on the monument (on the walls, pillars, vaults and *specus*) were analyzed using conservation-scientifc methods.

II. Report on the stay in Zaghouan / Tunisia from Oct. 17 – Nov. 07, 2021

Two parts of the monument structure were selected as study area :

1) The cella of the Roman spring sanctuary of the water pipeline in Zaghoan
2) A section of 12 pillars of the aqueduct structure in the Miliane valley

The first work at the office consisted in locating the monuments on the geographical map, to carry out the inventory work and to facilitate the tasks on the ground. The work on the ground required the perception of the monument from the inside and the outside, photos taking, and measurements (surveys), and the production of sketches.

On basis of a 3D laser scan prepared by the Austrian team member Irmengard Mayer, ortho projections of all surfaces and architectural sections were provided in the scale 1:50. Equiped with such detailed architectural plan material, the selected parts of the hydraulic complex were studied on site. All findings of the building archaeological and condition survey under the guidance of the academic conservator and Austrian team member Barbara Rankl were noted in mappings (material and damage mappings) and described in catalogues (masonry catalogue, identification of construction techniques). Under her direction, also nitrate and chloride tests were carried out on samples of damaged stones to learn the cause of degradation and to identify the nature of the stone. Subsequently, a legend was developed to represent the damage to the monument.

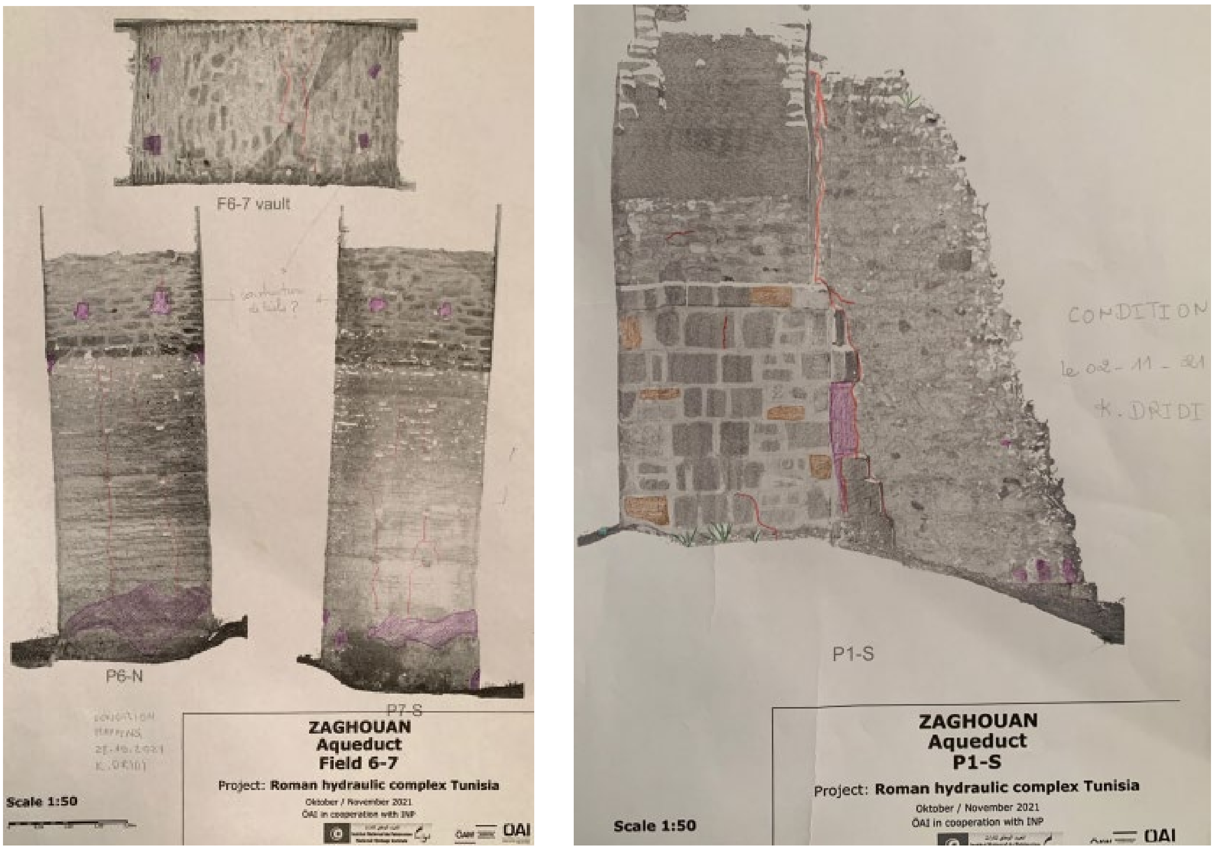

Fig. 1: On-site documentation work: inventory and condition mapping on basis of 3D laser scan ortho projections

Afterwards, the plan material of the documenation on site was digitized. As a result, a first inventory version of the selected study areas of the aqueduct and related buildings structures was available digitally. In the following, this data collection was used for detailed diagnosis and description of the historic structures.

After the field research stay in Zaghouan, to support the work on site, archival research was prepared at the National Archive of Tunis, looking for administrative letters containing useful information regarding the latest maintenance measures on the aqueduct structure. This was followed by an systematic biographical study. Those documents contained useful historical information on the situation of the aqueduct structure in the 19th and early 20th century:

- Administrative letters dating from the colonial period, around 1900, indicate that restoration work was carried out in 1878.
- A report by the antiquities department examining the condition of the aqueduct was sent to the deputy secretary of the Tunisian government on March 14, 1906. It says that the damage goes back a long way, and the aqueduct was once used as a stone quarry for the construction of numerous houses in Manouba - "spoliation".
- A document from 1906 studying the work carried out in 1895 states: The aqueduct had 87 pillars standing and 85 remain, noting that 2 pillars were destroyed in 1900.

	Wall 01-Restoration	Wall 02-Restoration	Variation of wall 02	Wall 03- Roman Arch	Wall 04- Roman "robbed"	Wall 05-Restoration
aterial-Stone	sand stone	sand stone		sand stone	Residues of sand stone	Sand stone
aterial-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
iggest ggregates grain imension	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
mallest visible ggregates grain imension	below 1 mm	1 mm		1 mm	1 mm	Below 1 mm
he 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
ool 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 / w brush Stone tool pointed chisel
oint 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 Vertica joint horizontal distance 4.5, 3, 4.5, 6.5
oint 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
tone 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, 26.5, 19, 19.5 Width : 2 30, 23, 8, 26
	sanding, scaling, erosion, microbiology : linches, black			Sanding, scaling, erosion , black biofilm , scratches (anthropogenic mechanical	Good condition no	good condition; no majo damages; one vertical

Fig. 2: Example of the data collection in the so called *masonry catalogue*

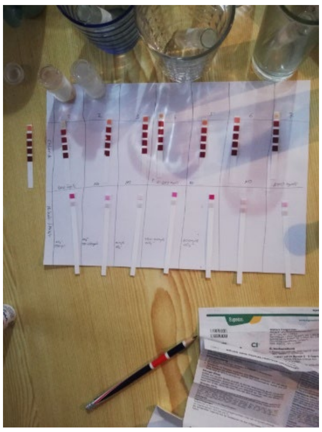

Fig. 3: Nitrate and chloride tests were carried out on damaged stone samples.

III. Report on the stay at OeAW-OeAI in Vienna / Austria from June 01–30, 2022

Projekt work

During the stay, missing parts of the documentation and inventory on site were digitized in AutoCAD and the inventory of the selected study areas of the aqueduct and related buildings structures was finalized.

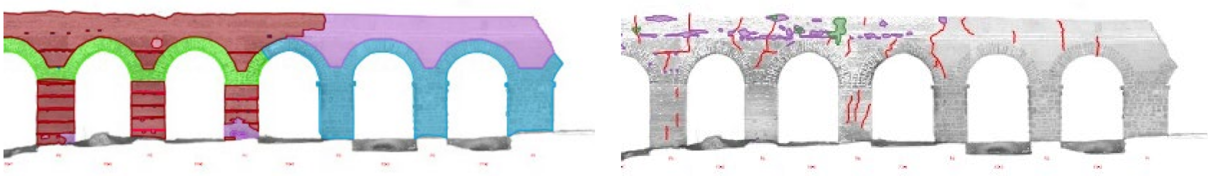

Fig. 4: Aqueduct section in the Miliane valley :
Mapping of construction materials (left) and condition / damages (right) of the structure

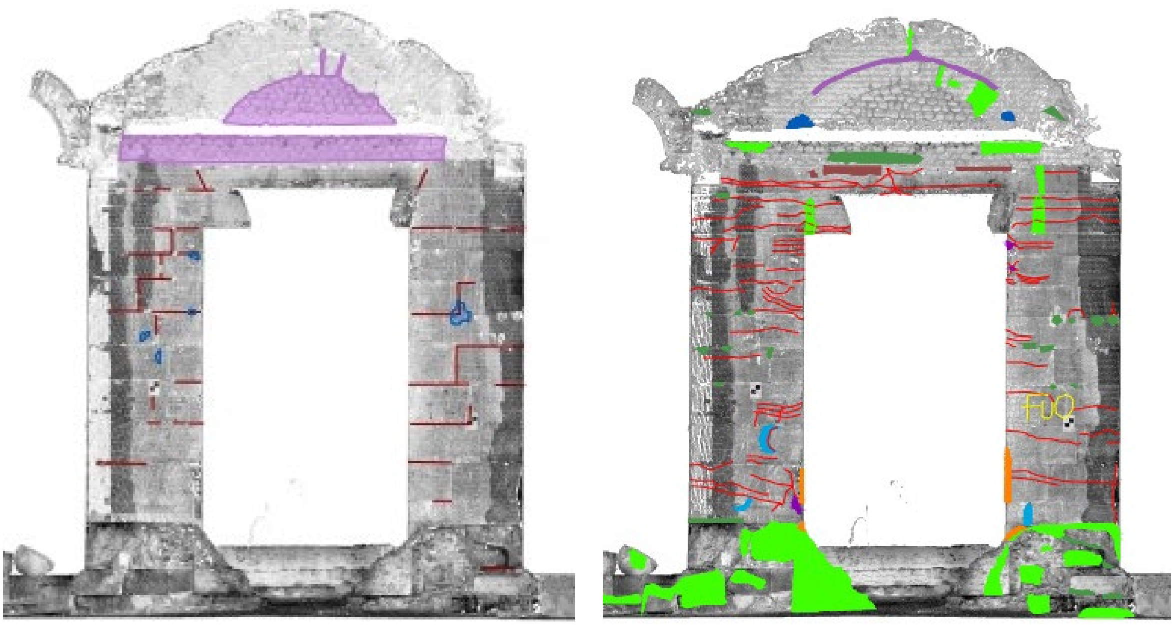

Fig. 5: Cella of the Spring sanctuary in Zaghouan, view of the facade: Inventory and condition mapping

One of the aims of the project is to date the various restoration measures carried out on the aqueduct over the centuries. To achieve this, we have relied on bibliographic works of significant historical value. So, I devoted a large part of my stay in Vienna to the study of those historic works written by Arabic-speaking authors who lived during the medieval period:

- bn Abī Dīnār, al -Mủnus fī aẖbār ifrīqyā ū tūnis,Tunis
- Al-Muqadima de Ibn khaldoun
- Muḥammad ibn Muḥammad al-ʻAbdarī, Riḥlat al-ʻAbdarī al-musammāt al-riḥlah al-Maghribīyah, Alger, manšurāt būna lil buḥt ū al-dirasāt

In addition, I also consulted a number of modern and current research publications related to the Roman hydraulic complex between Zaghouan and Carthage:

- Marcel Emerit: la pénétration industrielle en Tunisie revue africaine 1952
- Jean Ganiage, Les origines du Protectorat français en Tunisie (1861-1881), éd. Presses universitaires de France, Paris, 1959
- Baklouti (H.), 2003, »Les citernes de la Malga à Carthage. Plan d'ensemble et architecture«, Africa, Nouvelle Série, Séances Scientiiques, I, 2003, p. 129- 161
- Ithaf Ahl al-zaman bi Akhbar muluk Tunis wa 'Ahd el-Aman, 8 vol., éd. Secrétariat d'État à l'Information et à la Culture, Tunis, 1963-1966
- Di Stefano (G.), »Nuove ricerche sulle cisterne de La Malga«, in Contrôle et distribution de l'eau dans le Maghreb antique et médiéval, Rome, INP-ÉFR, coll. de l'École fr. de Rome 426, p. 143-164

The use of the institute library and access to portals with publications available online were a great help for research (also compare the bibliography).

<u>Training for postprocessing of 3D laser scan data</u>

I attended an introductory course on the postprocessing of 3D laser scan data presented by the responsible technician of the institute Ms. B. Danthine. This course gave me detailed information on the use of several software applications for the creation of architectural views and sections out of 3D laser scan data. During the field research, we produced the mappings and recorded the findings on site on the basis of such plans. The course now taught us which digital tools can be used to generate these orthogonal projections from the recorded 3D point cloud.

<u>Contacts at the OeAW-OeAI</u>

I came into contact with several people at the institute as researchers, architects and engineers who welcomed me. I am thankful for the interesting introduction on metal jewelery from the Byzantine period by Mr. David Schwarcz and the information I got from archaeologist Dr. Alice Waldner, head of the research group ″Object intineraries″.

<u>Cultural activities</u>

In addition to the project work, I used my stay in Vienna for cultural excursions such as museum visits and visits to famous churches like St. Stephen's Cathedral or a visit of the opera.

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5_ ARNAUD (J-L), DELPAL (CH) Grangaud (I), ***l'urbain dans le monde musulman de méditéranée,*** publier 2006

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7_ J.-P. Van Staevel, ***Réflexions à propos de la nomenclature médiévale de l'architecture de terre en Occident musulman : l'exemple du tabiya. Dans L'architecture de terre en Méditerranée,*** Actes du colloque de Rabat (Maroc), 27-29 novembre 1996, Université Mohamed V, Série colloques et séminaires, n° 80, Rabat, 1999, p. 95-96

8_ BENOIT (F), ***l'architecture l'orient medieval et moderne***, Paris 1912

9_ M. Ibn Hauqāl,***ṣūrat al-arḏ***, dar maktabat al-ḥaiyāt, Liban 1992

10_ BOURGOIN (J)***, Précis de l'art arabe et matériaux: pour servir à l'histoire,à la théorie et à la technique des arts de l'Orient Musulman***, publié 1892

11_ Choisy (A***), Vitruve, I,*** Paris 1919

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14_ ***Ithaf Ahl al-zaman bi Akhbar muluk Tunis wa 'Ahd el-Aman,*** 8 vol., éd. Secrétariat d'État à l'Information et à la Culture, Tunis, 1963-1966

15_ Marcel Emerit: ***la pénétration industrielle en Tunisie***, Revue Africaine 1952

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Geometrical and building historical documentation and analysis of the Roman hydraulic complex in Zaghouan and the Miliane Valley (Tunisia)

Irmengard Mayer

October / November 2021

Abstract

Within the frame of the project *Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia)*[1] the first field campaign took place in October/November 2021 lasting three weeks. The main goal of this campaign was the geometrical three-dimensional and building historical documentation an analysis of exemplary sections of the Roman hydraulic complex around Zaghouan. On one hand the Water Temple in Zaghouan as starting point of the aqueduct was chosen and on the other hand a short section of 12 pillars from the aqueduct in the Miliane Valley (36°38'05,0"N 10°07'43,7"E according to Google Maps). 3D surveying techniques were used for the documentation and to support the building historical analysis. In this way, it was possible above all to identify the construction technique and beyond the work sequence in the erection of the medieval pisé pillars.

Keywords

Laser scanning, photogrammetry, building history, antique building techniques, medieval building techniques, Zaghouan, Tunisia,

Activities

The Roman hydraulic complex between Zaghouan and Carthage lays in the focus of this one-year exploratory project. Exemplary areas for documentation were chosen to examine the possibilities of documentation. At the first field campaign at altogether three

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[1] The project was organised as a cooperation between the Austrian Archaeological Institute (OeAI), situated at the Austrian Academy of Science (OeAw), and the National Heritage Institute (INP) of Tunisia and is founded by the Austrian Agency for Education and Internationalisation (OeAD). The project was led by Dr. G. Styhler-Aydın (OeAI) and co-coordinated by Dr. H. Ben Romdhane (INP). The conservation-scientific investigation was carried out by B. Rankl (OeAI), K. Mighri (INP) and K. Dridi (INP). The work on the geometrical and building historical documentation and analysis was done mainly by I. Mayer (OeAI) supported by Dr. G. Styhler-Aydın, B. Rankl, K. Mighri and K. Dridi.

segments were surveyed for various reasons. The Water Temple at Zaghouan needed to be documented due to the actual bad condition and static problems arising from a crack in the architrave of the entrance to the cella. At the Miliane Valley a segment of 12 pillars shows different building phases, construction methods, reconstruction methods of different time periods. The state of conservations reaches from almost perfectly preserved to almost destroyed. This aqueduct segment was supplemented by the documentation of two building components with preserved specus north of the 12 pillars.

Fig. 1: Overview of locations of surveyed objects in the region of Zaghouan

The cooperation with the project members of the National Heritage Institute of Tunisia (INP) at the first field campaign provided information about historic restoration measures carried out, especially for the building historical analysis of the individual segments. Their support during the survey and at the material and damage mapping provided the base for both further investigations into construction techniques and the sequence of construction as well as for the conservation-scientific inventory and condition survey.

METHODS USED

For the documentation and analysis of the selected areas at the district of Zaghouan and at La Malga in Tunis different methods established in the field of building documentation and analysis since many years were deployed.

The survey was performed by the following hardware:

- Laserscanner Faro Focus 3D 120S (without use of camera)
- Leica TS07 Totalstation
- Sony ILCE-7MR3, 50mm lense

The postprocessing was executed by using the following software:

- IDC Geosi Verm 16.0.35.51
- Faro Scene 2019.2
- Agisoft Metashape Professional 1.7.3. build 12473 (64bit)
- AutoCad 2020 – German

The survey by the terrestrial laser scanner as well as the photogrammetric survey was supported by a tachymetric survey. Since no higher-level coordinates were available all measurements are in a local coordinate system and not georeferenced. Nevertheless, thanks to the tachymetric polygon track, all measurements (laser scan and photogrammetric survey) of each single segment surveyed are in the very same local coordinate system.

The 3D dataset delivers the necessary information for the creation of 2D plans and orthogonal projections. For the 2D plans all necessary vertical and horizontal sections were created, brought into scale, and printed. The orthogonal projections were prepared in the same way for all visible and surveyed surfaces. For both the sections and orthogonal projections the information was densified on site. The former enabled the detailed representation of construction details and the latter served as a basis for the conservation-scientific inventory and the condition survey.

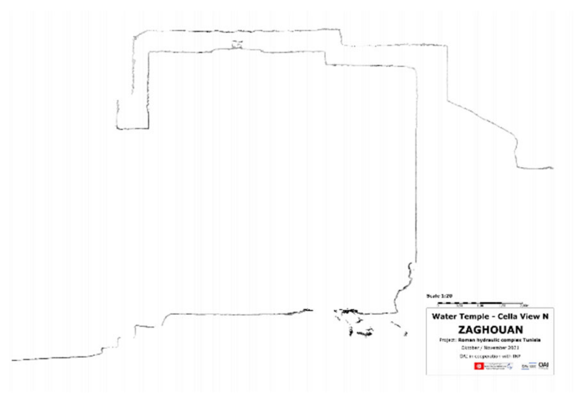

Fig. 2. cross section through the 3D point cloud of the Water Temple

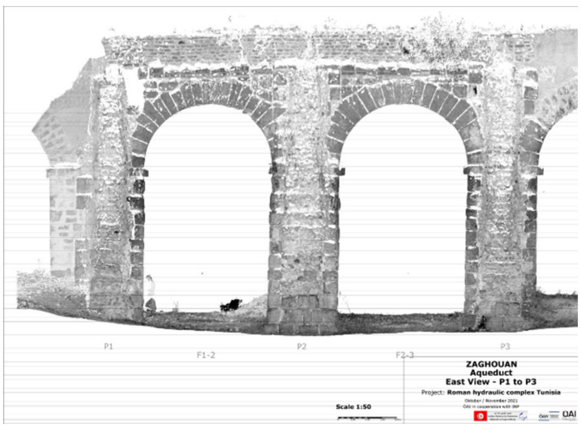

Fig. 3: orthogonal projection of the 3D point cloud of pillar P1 to P3 of the aqueduct section

Results and Discussion

At the first field campaign the main focus was set on the construction details and methods as well as on the development of a relative chronology of the relatively short segment of the aqueduct in the Miliane Valley. This short segment of the aqueduct shows the building history from Antiquity to the Middle Ages. The most important observations are briefly described below.

Aqueduct Miliane Valley, 12 Pillars

The selected section of the aqueduct in the Miliane Valley is about 80m long and stands up to a height to 11,5m. 12 pillars support a total of 11 arches on which the specus for the water conduit runs. The pillars, the arches and the specus represent different time periods (Roman, medieval, modern), different construction techniques (ashlar masonry with opus caementicium, rammed earth) and several modern restorations. The specus itself is only partially preserved and was not accessible for recording due to the height of the aqueduct.

East of the four southern-most pillars (P1, P2, P3 and P4) supporting walls in different state of conservation are preserved. The northern-most supporting wall (P4) is detached of the medieval pillar (rammed earth structure) while the remaining three pillars are still interlocked with the Roman supporting walls. Supported by several references, it can be stated that the aqueduct was built without the supporting walls. However, the building material and construction techniques show that the supporting walls were added during antiquity.

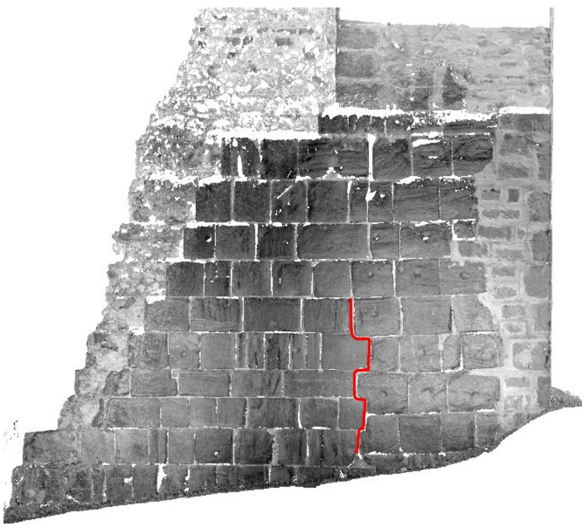

Fig. 4: P2-N, shifted horizontal joints with collision of masonry of pillar and supporting wall

Fig. 5: marks of lifting tool ("Zangenlöcher")

The most striking clue is that the opus caementicium covers the stones of the arches. Another clue are the horizontal joints of the supporting walls which lay on a different height than the horizontal joints of the pillars. To allow the stones of the pillar and supporting wall to interlock, the corner stones of the pillars were removed, and edges were partly worked out on the stones of the pillar. The marks of a lifting tool ("Zangenlöcher") in the stones of the pillars and the supporting walls give another hint for secondary construction

Nine of the altogether 12 pillars are built in pisé and have a distinctive external appearance. Pinkish layers of a height of about 85cm ± 5cm alternate with white highly chalky levelling layers of about 5cm to 10cm. Due to the necessary height of the impost for the vault the upper most layer of pisé varies in height. It can be assumed that the beam holes (width ~10 to ~15cm, height ~5 to 8cm, depth ~65 to ~80cm) below the levelling layers are remains of the formwork used to make the pisé pillars.

Fig. 6: Pillar 4 west face, rammed earth with levelling layers

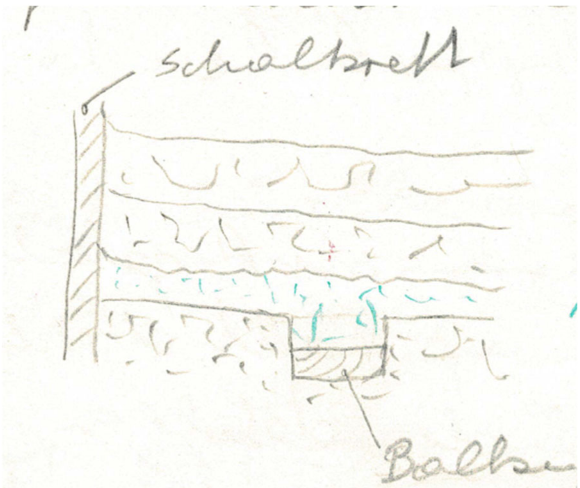

Fig. 7: cross section through pisé pillar with formwork and beam

Each pinkish earth layer consists of 9 to 10 courses. Each of these courses was poured individually and compacted to an average height from 8cm to 10cm. The bottom course was applied damp on top of the levelling layer, which was also still damp. This is indicated by the good connection between the top of the levelling layer and the lowest course of rammed earth. On the other hand, it can be seen on the lower edge of the levelling layer that there is no connection between the rammed earth and the levelling layer. Rather, a clear separation is visible at the lower edge of the levelling layer and an edge is created. This could be the result of pouring the levelling layer on the almost completely dry last course of rammed earth. At the corners of the pillars, the levelling layer and the individual courses of the pisé rise somewhat, which can be attributed to the difficulties of compaction in the corners of the formwork.

About 1,8km north of the 12 pillars remains of a vaulted specus are visible (according to GoogleMaps: 36°39’02,4”N, 10°08’00,2”E). The pillars only rise about 2 metres from the ground and a longer piece of the specus with vault is preserved. The specus also shows clear evidence of re-use.

The three-week stay in October 2021 provided a good insight into the various water engineering structures of Roman antiquity in Tunisia. With the focus on one section of the aqueduct, it was possible to examine building materials and techniques from the construction phase in antiquity as well as those of the medieval re-use phase. The building historical research of the chosen segment enabled, on the one hand, new personal insights into regionally applied building techniques of the Romans and, on the other hand, the establishment of new contacts to the INP and its staff for the preparation of further research projects.

List of Illustrations

Fig .1 Google Earth

all other figures by Irmengard Mayer

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Geometrical and building historical documentation and analysis of the Roman hydraulic complex in La Malga, Tunis (Tunisia)

Irmengard Mayer
March 2022

Abstract

Within the frame of the project *Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia)*[1] the second field campaign took place in March 2022 lasting three weeks. The main goal of the second campaign was the geometrical three-dimensional and building historical documentation an analysis of a selected area of the Roman cistern at La Malga in Tunis as well as of the remains of the aqueduct close the cistern. The same 3D surveying techniques were used as in October/November 2021. In addition, the mapping of the aqueduct in the Miliane Valley was digitised based on a consistent key. This work was mainly carried out by the project members of the National Heritage Institute of Tunisia (INP).

Keywords

Laser scanning, photogrammetry, building history, antique building techniques, medieval building techniques

Activities

The Roman hydraulic complex between Zaghouan and Carthage lays in the focus of this one-year exploratory project. Exemplary areas for documentation were chosen to examine the possibilities of documentation. At the second field campaign three spots at the site of La Malga were surveyed for different reasons. Although the La Malga cistern is not connected to the aqueduct coming from Zaghouan, it was part of the documentation. The documentation was done at the compartments 12 and 13 of the cistern where

[1] The project was organised as a cooperation between the Austrian Archaeological Institute (OeAI), situated at the Austrian Academy of Science (OeAw) and the National Heritage Institute (INP) of Tunisia and is founded by the Austrian Agency for Education and Internationalisation (OeAD). The project was led by Dr. G. Styler-Aydın (OeAI) and Dr. H. Ben Romdhane. The conservation-scientific investigation was carried out by B. Rankl (OeAI), K. Mighri (INP) and K. Dridi (INP). The work on the geometrical and building historical documentation and analysis was done mainly by I. Mayer (OeAI) supported by Dr. G. Styler-Aydın, B. Rankl, K. Mighri and K. Dridi.

archaeological sections have been done and the bottom of the compartments was almost excavated. This allowed a detailed survey of the cross section through the two vaults and the drain channel in-between. In order to be able to make comparisons with the already documented section in the Miliane valley in terms of construction technique, chosen building materials, damage patterns and restoration measures, three pillars of the aqueduct including the specus south of the cistern were surveyed and documented in La Malga.

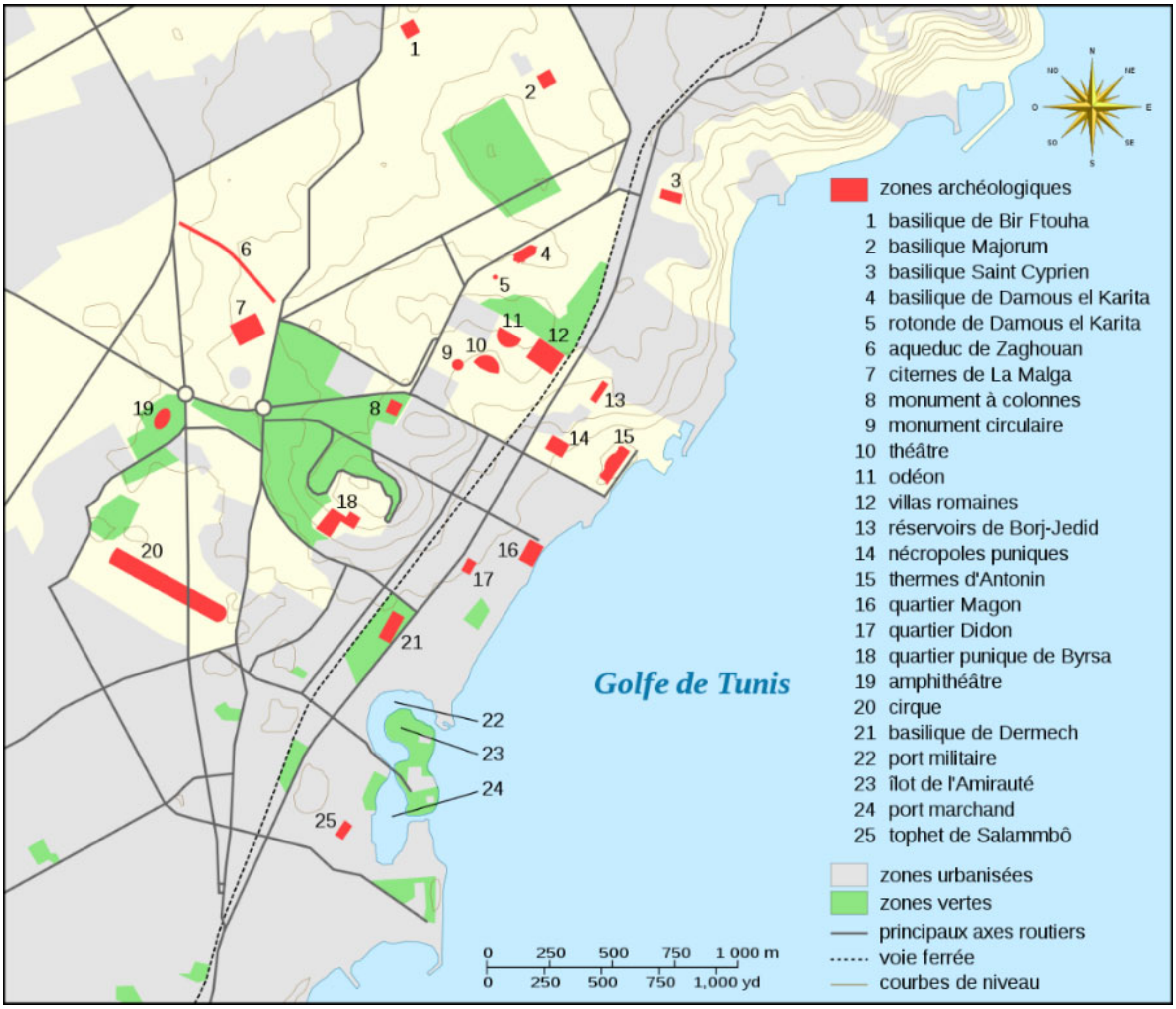

Fig. 1: Plan of Carthage archaeological site (Author: Eric Gaba – Wikimedia Commons user: Sting)

The members of INP provided again information about historic restoration measures. They supported the material and damage mapping for further investigations on construction techniques and the sequence of construction as well as for the conservation-scientific inventory and condition survey of the surveyed spots at la Malga. INP team members also carried out much of the digitisation of the October 2021 mapping from the Water Temple at Zaghouan and the aqueduct section in the Miliane Valley.

Methods used

For the documentation and analysis of the selected spots at La Malga in Tunis the very same surveying and post-processing methods like in October 2021 were deployed. The table below shows the effort required for both campaigns for the tacheometric survey and the geometric documentation using the 3D laser scanner and photogrammetry.

	polygon points	surveyed targets	scan positions	photogrammetric survey
Water Temple, Zaghouan	2	11	44	1.064 pics
aqueduct Miliane Valley – 12 pillars	4	9	71	1.821 pics
fallen specus	-	-	7	-
aqueduct Miliane Valley – vaulted specus	-	-	43	-
La Malga	4	-	-	-
cistern – compartement 12 and 13	-	6	58	-
aqueduct pillar 26 to 28	-	5	30	-
aqueduct east of pillar 1	-	4	14	-

Tab. 1: Survey

Results and Discussion

Within the second campaign the main focus was set on the construction details and methods of the cistern at La Malga. A short segment of the aqueduct south of the cistern and the intersection of the Roman aqueduct east of pillar 1 with a higher pipeline. The most important observations are briefly described below.

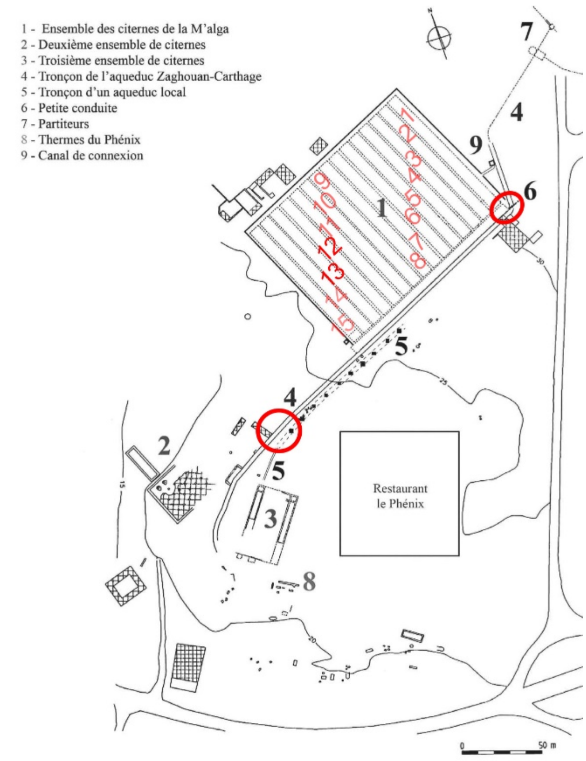

Fig. 2: areas of interest at the complex of La Malga (plan according to Baklouti 2019c, 3 fig. 2)

Fig. 3: cistern – compartments 12 and 13

AQUEDUCT AT LA MALGA

Parallel to the cistern in a distance of about 4m runs the antique aqueduct coming from North and leading to South-West. All together 28 pillars starting from North are part of one section of the aqueduct interrupted only by a roadway. The south façade is almost completely reconstructed only the arches between P9-P10 and P20-P21 are robbed and the core of opus caementicium is visible. Only between P7-P8 and between P8-P9 the antique arch is still in place. Each stone layer of these arches is laid wedge-shaped in regularly dressed sandstones and consists of a longer (width from 52 cm to 56 cm) and shorter (width from 33,5 cm to 40 cm) stone whereas the butt joints are staggered. The spandrels show improperly layered masonry.

At the upper edge, below the sole of the specus a layer of grey stones is visible at the façade and serves as a levelling layer. However, this levelling layer does not extend through the entire aqueduct but can only be observed on the two facades. The channel of the specus is preserved over almost the entire length of the selected segment. In the North, in the curve of the aqueduct towards northwest, both walls and the barrel vault of the specus are preserved for a short distance.

Fig. 4: aqueduct, preserved antique vault between pillar P8-P9 in the foreground and robbed vault in the background

Fig. 5: aqueduct, row of grey stones below the sole of the specus

CISTERN AT LA MALGA

Fig. 6: cistern, drain channel between compartments between 8 and 9, structure and thickness of different plaster layers

Fig. 7: cistern, drain channel between compartments 9 and 10 southern preserved section, on the vault of comp. 9; clay pipe is covered by opus signinum

The cistern consists of 15 parallel compartments separated by walls and each compartment is covered by a barrel vault. The north and south side of each compartment was closed with a shield wall as well as the spandrels between the vaults were closed by a spandrel wall. These walls are partially destroyed. The water engineering construction details suggest that the cistern was built only for the collection of rainwater. Between the vaults drain channels collected the rainwater which is transported by clay pipes into the compartments. Clay pipes were placed during the building process on top of a levelling layer at a regular distance of around 5,7m to bring the rainwater from the drain channels into the compartments.

Two different layers of plaster respectively surfaces are preserved in the drain channel. On the first layer sintered lime layers are visible. The lower edge of the clay pipe described above lays a few centimetres above the sole of this first surface of the drain channel. The second layer of plaster with unusually large stones and brick chippings lays on top of the sintered lime layers and forms a bead in the corners between the sole and the barrels. In the drain channel between compartment 9 and 10 the remains indicate that the upper layer of plaster initially covered the clay pipes completely. This suggests that the second layer of plaster was applied when the cistern no longer had its original function or was not used in its original form anymore.

The two three-week stays provided a good insight into the various water engineering structures and techniques of Roman antiquity in Tunisia. There are both similarities and clear differences in the choice of materials and construction techniques between the different surveyed segments. The medieval after-use of the hydraulic systems is also clearly reflected in a deviating building technique – rammed earth construction.

List of Illustrations

Fig. 1 https://en.m.wikipedia.org/wiki/File:Carthage_archaeological_sites_map-fr.svg; Author: Eric Gaba – Wikimedia Commons user: Sting

Fig. 2 plan according to Baklouti 2019c, 3 fig. 2

all other figures by Irmengard Mayer

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

Combined Report on the

- **Stay at Zaghouan from October 17-November 07, 2021**
- **Stay at OeAI Vienna from June 01-30, 2022**

Khaoula Mighri
September 2022

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Introduction :

The Zaghouan-Carthage hydraulic complex is one of the best-designed and most ingenious complexes in the Roman world. Its aqueduct which connects between Zaghouan and Carthage, is the longest among the Roman aqueducts with a length of 132 km and such remarkable and inventive architecture. The cisterns of this complex are among the most important Roman cisterns with a capacity of almost 44000m3.

This exceptional work of art testifies to an ancestral know-how that has developed over the centuries with different phases of construction and repair where the builders had recourse to the use of several materials and constructions techniques.

Since 2012, the entire Zaghouan – Carthage hydraulic complex has been included on the tentative list of UNESCO World Heritage Sites. [1] Research works are then maintained to help to have the necessary and sufficient conditions for the inscription of this important hydraulic construction complex on the list of the world heritage of UNESCO and it is in this context that our project of investigation of the Zaghouan-Carthage hydraulic complex, the aim of which is to provide richer and more oriented documentation and more effective scientific research on well-chosen elements of this complex to help in its inscription on the UNESCO World Heritage List.

[1] http://whc.unesco.org/en/tentativelists/5685/ (last access: 07.09.2022).

I- Project presentation:

Our project: "Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia)" is carried out within the framework of research cooperation between the Austrian Archaeological Institute (OeAI) and the National Institute of Tunisian Heritage (INP). The studied area of this hydraulic complex covers elements that are installed throughout this structure. At the beginning of our project, we started our work in the water temple at Djbel Zaghouan, only the cella and part of the two galleries were chosen. In its middle, at the level of the valley of Oued Miliane, a section containing 12 pillars of the zone overlooking the road GP3 was chosen, and at the point of arrival of the canal in Carthage, in the zone of La Maalga, two cisterns and a section of the aqueduct which passes in front were chosen for our investigation.

Our field has focused on two aspects: the inventory of the different construction materials and the state of conservation of the chosen areas.
The construction phases identified are essentially three major phases of construction and use of the hydraulic complex: Antiquity and Late Antiquity (2nd-7th century), Middle Ages (12th century Hafsid repairs), modern period and contemporary repairs.
The project lasts one year and is divided into four stages:

Step 1: Research stay in Tunisia. Fieldwork in Zaghouan from October 17 - November 07, 2021 ; documentation of the building and the scientific inventory of the conservation of the section of the aqueduct selected in the Oued Miliane valley.

Step 2: Field research in Maalga/Carthage from March 06- 27, 2022: documentation of selected building structures including scientific inventory at the Maalga cisterns and a selected section of the adjacent aqueduct. Digitization work on Autocad.

Step 3: Research stay in Vienna from June 1 – 30, 2022: Finalization of the digitized documentation work and analysis of archive material

Step 4: Final Workshop, discussions and preparation of the publication.

II- General work methodology:

1- Stay at Zaghouan from October 17- November, 2021

In situ mapping
For this phase of work, we proceeded by analyzing the structures of the complex selected on site with the development of a scientific inventory of the construction materials and the state of conservation.
The mapping method has been defined for the different areas of the site selected and an exhaustive graphic documentation of the different elements has been well established. The mapping method used for this project can be summarized in the inventory of building materials, the construction details, the state of conservation and the various degradations observed at the level of the structures chosen for study and the development of certain scientific tests on the materials on site with the identification of their location with the method of degradation.

For each zone, a very precise legend has been developed which depends on the specificities of each structure inventoried.

For the mapping work, plans generated from 3D laser scanning produced by I. Mayer were used as a background on which each color indicates either a type of material (inventory mapping) or a degradation (condition mapping), and for the elaboration of this work a caption has been adopted.

Fig. 1: On-site documentation work: inventory and condition

Significant graphic documentation was developed *in situ* with the identification of the various degradations and construction materials with pictures and measurement of the various construction elements: length and width of the stones, thickness of the mortars, joints etc.

<u>Digitization work on Autocad software:</u>
After completing the field work, we proceeded to the digitization work on the Autocad software. A unified legend was chosen and we mainly focused on the parts of the aqueduct and the cisterns in Maalga. The digitization of the mapping at the level of the water temple in Zaghouan only concerned the interior and exterior of the Cella.

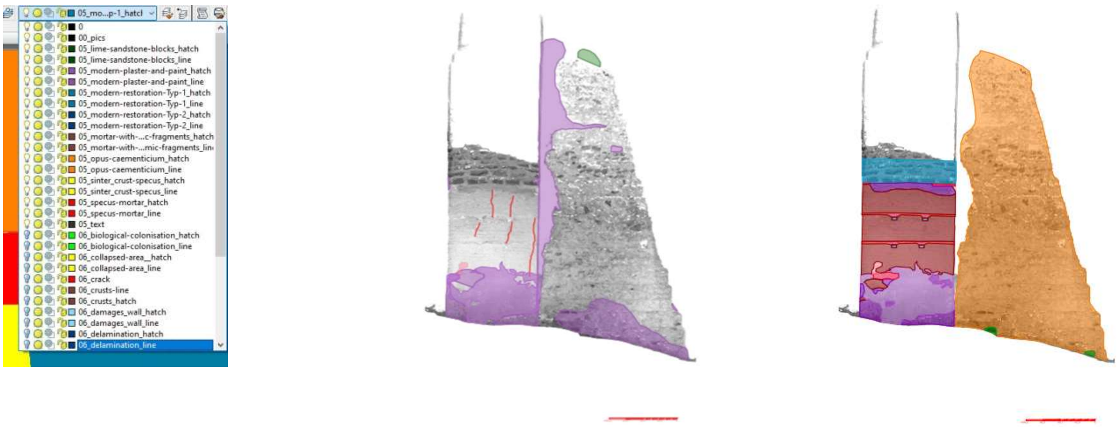

Fig. 2: Example of work done on Autocad : Inventory and condition

2- Stay at OeAI Vienna from June 01-30, 2022

The digitization work was initiated during the October/November mission 2021 and the March 2022 mission, where the work was divided into two parts: on site work in the field and office work with the digitization of plans, elevations and mappings. Given the very large volume of elements to be digitized, we could not complete all the work requested in March and we left the last part for the Vienna mission to be finalized.

For each element of the structure, two maps were digitized: one for the construction material and the other for the state of conservation and the various degradations identified at these constructions.

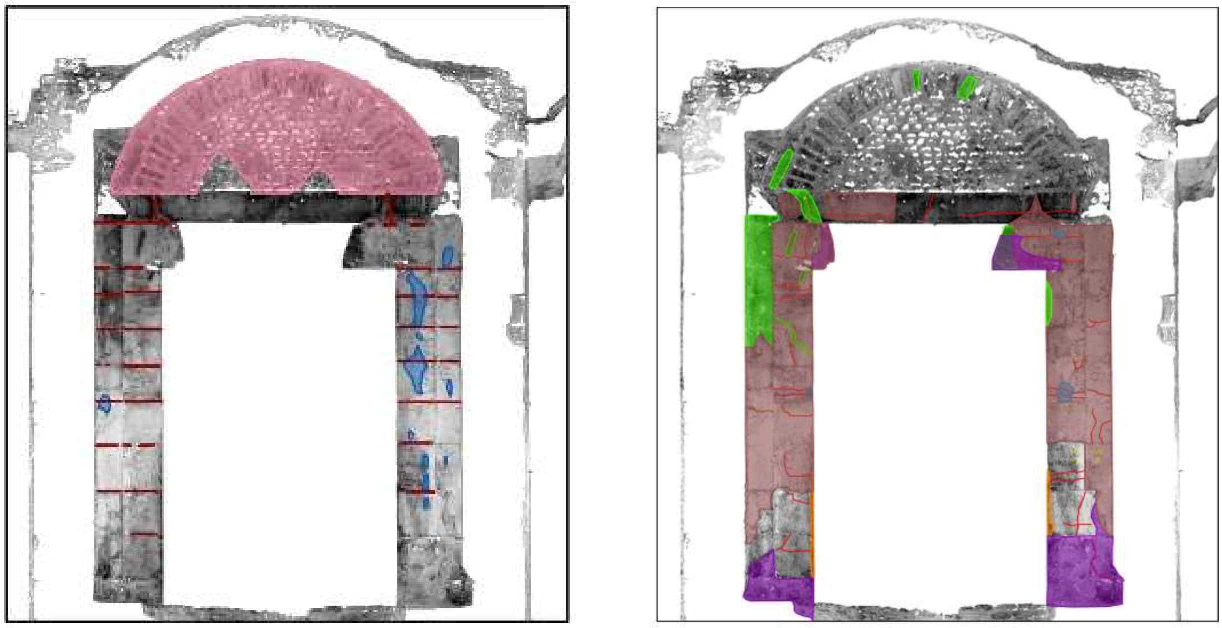

Fig. 3: Digitization of the inventory and condition mapping carried out on the Cella of the spring sanctuary in Zaghouan (interior view of the wall with entrance)

Fig. 4: Digitization of the inventory and condition mapping carried out on the aqueduct section in the Miliane valley

III- Report on the Zaghouan Stay in October/November 2021

1- Stay and work organization

As there was no INP workplace available in Zaghouan, a private house was rented for the duration of the stay. It provided comfortable accommodation for all team members and also allowed workstations to be set up for the digital preparation and follow-up of the field research.

After the team members had met and got to know each other in person for the first time, the planned work packages for the field research were discussed. The team dedicated the first few days to a section of the spring sanctuary in Zaghouan. Work then shifted to a section of the aqueduct in the Miliane Valley.

2- Documentation and Analysis on site

At the spring sanctuary of Zaghouan, the cella was analyzed and documented with regard to the building materials used, the underlying ancient construction technique and the current state of preservation. A scientific and conservational assessment of all wall,

floor and ceiling surfaces was carried out under the guidance of B. Rankl using the plans generated by I. Mayer on basis of an 3D laser scan.
The same procedure was also used to analyze a section of the aqueduct in the Miliane Valley. However, this involved more complex construction sequences and repair and restoration phases (see II-1).

3- Presentation of first results

At the end of the first phase of field research in the project, a workshop summarized the preliminary results in the form of individual presentations (see Fig. 3-4). The work packages for the next research visit were also discussed.

IV- Report on the Vienna Stay in June 2022

This stay in Vienna was established with the aim of achieving a transfer of knowledge on the methods used in field research for building documentation and analysis for Tunisian team members. The stay lasted one month, during which my personal experience was very rich and fruitful, especially with the contact established with Austrian colleagues and the discovery of their work methodology and their exemplary organization. Due to the circumstances of the Covid-19 pandemic and our postponed visit, the planned training in the use of the laser scanner and photogrammetry software had to be shorten, unfortunately. It was however possible to take advantage of colleague assistance at ÖAI and the presence of a rich library. I was also able to take advantage of the institute's network to carry out a bibliographical search for the planned project publication.

1- Reception at OeAI and logistics

The project leader, Dr. Gudrun Styhler-Aydın, welcomed us and accompanied us to the OeAI. When my Tunisian colleague and me arrived, everything was well organized and we were put in an office with an Austrian colleague. We settled in well and took the keys to the office to be able to enter and leave the building. We then toured the offices to meet the Austrian colleagues, and they were all very friendly and welcoming.

Fig. 5: The address of OeAI in Vienna 2022

Fig.6: Interiour view of the OeAI

Fig. 7: The office where we stayed during our mission at OeAI

2- Training in postprocessing of 3D laser scan data

During the stay, I took advantage of a short training session presented by the OeAI technician responsible for the postprocessing of 3D laser scan data. She showed me the handling of Faro software and how to obtain 3D images from point clouds.
Although, the time was too short for intensive training, but I was able to learn the principles practically all postprocessing software work with and that allowed me to become more familiar with this technology.

3- Finalization of the digitization work in Autocad

The stay in Vienna was also used to compare, complete and finalize the digital version of the documentation of the findings from the previous two fieldwork visits among all the team members. A complete set of plans of the investigated building and aqueduct sections is now available (see II-2).

4- Systematic literature and archive research

Systematic literature and archive research formed part of the scientific processing of the project. The results of this research in the INP photo library and INP archive were evaluated and discussed in the context of the findings on the building structures themselves. Particular attention was paid to post-antique information on historical construction and repair work. An overview of the information is shown in Fig. 8.

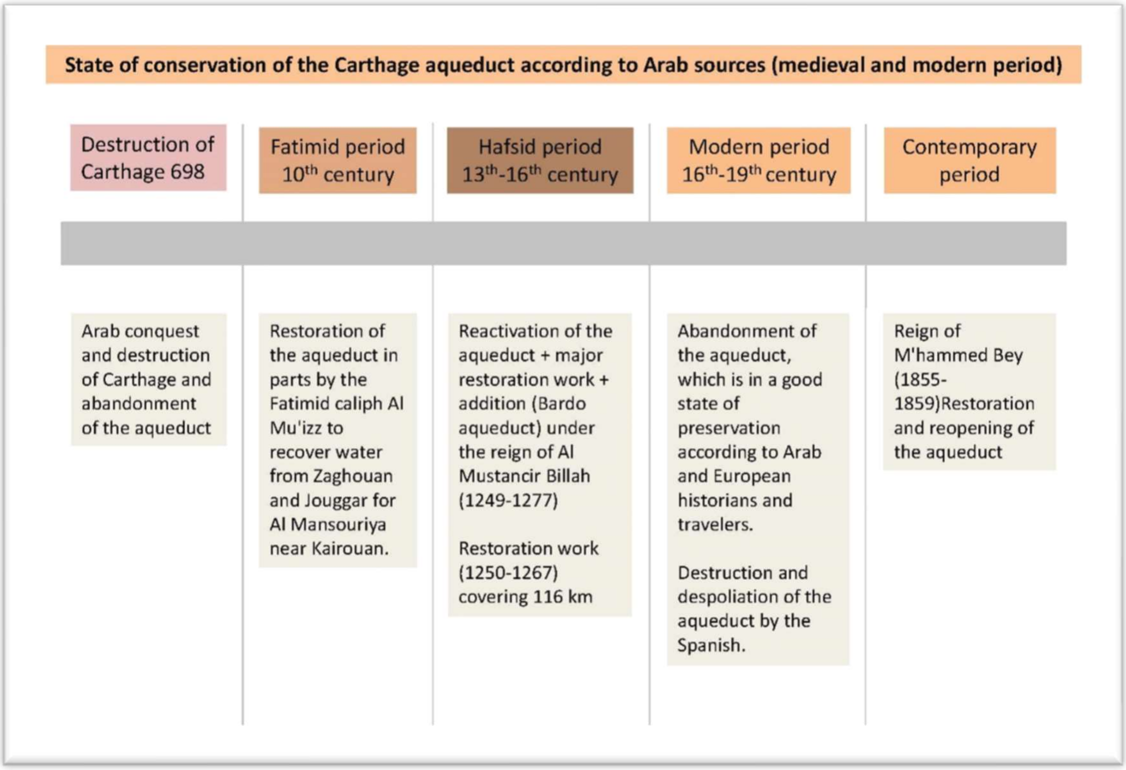

Fig. 8: Information on the aqueduct from historical sources after antiquity

 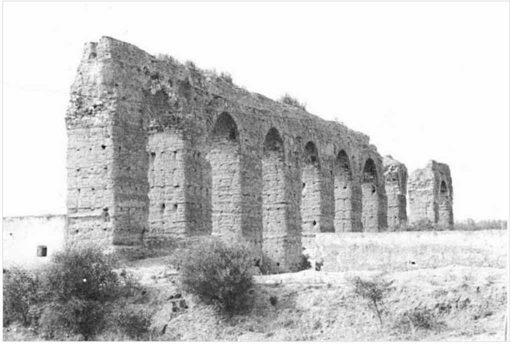

Fig. 9, 10: Historic photos of different sections of the aqueduct structure (INP photo library)

5- Workshop with presentation of the results of team and personal work:

The final workshop was organized and run by the head of the project in collaboration with all project members. The aim of the workshop was to exchange our latest work and the results of our established research, and to take stock of what has been achieved so far and what remains to be completed. During the workshop, we set out the main points and an outline of the structure of our planned publications based on the results obtained. We discussed how to broaden further scientific exchange and collaboration in the frame of future projects.

Conclusion:

The tasks accomplished during this stay including the presentation of the final results of the work and all the discussions established between the team members allowed me to have a deeper understanding of the objective of this cooperation between the OeAI and INP. The chosen approach, starting with the selection of the structural elements of the hydraulic complex and the methodology applied during the fieldwork to the library and archiv research, gives a solid basis for dealing with this type of project and issues.

To participate in the project allowed me to acquire the necessary knowledge to develop and support a concept for the preservation of the Zaghouan – Carthage hydraulic complex.

The final results of this project will certainly contribute to the process of nominating this complex to the UNESCO World Heritage List.

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

12 Pillars of Aqueduct, Oued Miliane Valley and Cella of Water Temple, Zaghouan

Report of on-site conservation-scientific investigation

Barbara Rankl

October / November 2021

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Introduction

As part of the project "Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia)" the first campaign on site in Tunisia was carried out. The project is implemented through a cooperation between the Austrian Archaeological Institute (OeAI) at the Austrian Academy of Sciences (OeAW) and the National Heritage Institute (INP) of Tunisia and funded by the Austrian Agency for Education and Internationalisation (OeAD). During the three-week stay from 17th October till 7th November 2021 the executed tasks were the high-tech field survey through 3D laser scanning and the conservation-scientific inventory and condition survey of selected object sections. The chosen objects demonstrated the cella of the Water Temple in Zaghouan and 12 pillars from the aqueduct in the Oued Miliane Valley. This report deals with the conservation-scientific survey and the output determines the basic components for the development of preservation concepts. The Austrian and Tunisian team members worked closely together in all steps. The investigations were carried out by B. Rankl (OeAI), K. Mighri (INP) and K. Dridi (INP) under the supervision of the project leaders Dr. G. Styhler-Aydın (OeAI) and Dr. H. Ben Romdhane (INP). The topics of building research and conservation science partially overlap, so that the collaboration with I. Mayer (building researcher, OeAI) on site was extremely fruitful. The report is structured as follows. First the methods implemented will be presented and afterwards the preliminary results from the gathered data during the work on site will we explained.

Methods

For the conservation-scientific investigation of the inventory and condition of the building structures, already beforehand, a set of methods were discussed and selected. The methods implemented during the field campaign focused only on on-site inspection using non-destructive methods.

Written and photographic documentation

First, a written inventory and condition survey of the selected areas was carried out and placed in the context of the entire building structure. A photo documentation of all building materials, processing traces and constructional manufacturing details as well as the most common damage patterns was made. For the classification of damage patterns the English-French version of the "Illustrated glossary on stone deterioration patterns" from ICOMS-ISCS was used.

Inventory and Condition Mapping

This established method in the context of preservation of monuments and building diagnostics provides comprehensive and clear information of the current situation found. Mapping is essential for the inventory and condition recording and demonstrates an indispensable instrument in the context of planned and consequently executed restoration projects. It assists in the compilation of a treatment concept and the documentation of restoration measures as well as the condition assessment before and after the restoration. Additionally, samples taken and areas to be examined for on-site test procedures can also be precisely localized. Mapping is an important basis for monitoring.

At the beginning of the work on-site areas for mapping were determined. Mapping represents the graphic documentation of defined categories. Within the scope of this project, mapping was limited to the building material, construction details, damage patterns and localizing of on-site material-scientific tests. The defined categories always depend on the specific inventory and condition of the individual site. Each category is assigned a colour. The basis plan is provided by Ortho-views of 3D laser scan data, which were produced by I. Mayer. Due to the difficult accessibility and the limited time, it was decided to map the rising masonry surfaces. For the detailed mapping a close up investigation is in general necessary. This precise examination could only be carried out in the first 2 Meters (m) above the walking horizon in front of the building structures. A more superficial mapping with the help of binoculars and selectively with ladder was carried out on the areas above 2 m. All data gathered has to be assessed according to this setting.

On-site material-scientific analyses

Next to the expertise of the stone conservator via optical and haptic investigation, on-site material-scientific analyses were carried out to support the overall diagnosis. The selected methods are non-destructive and easy to carry out on-site.

In order to support a general classification into the chemical composition of mineral materials, chemical analysis using hydrochloric acid (9% in water) is carried out. A drop of this liquid is placed on the surface to be examined. In the chemical reaction with lime, the liquid foams up. This is an indication that the material contains lime and this information can assist in determining materials such as stones, crusts and deposits.

The second method executed were salt tests. Salts, when infiltrating the structure of the building can cause damages, for example due to the crystallisation of the salt minerals. The presence of salts on the objects were verified with test strips. The areas or fragments to be examined were scratched off the surface with a scalpel and stored in a glass vessel which was filled up with water. After 10 to 30 minutes, the liquid with the possibly dissolved salt was examined using test strips. In the case of presence of salts, the test strips react with a colour reaction. The investigation of the selected areas comprised a total of four different anions (Chloride, Sulphate, Nitrate, Nitrite), which occur most frequently in connection with harmful salts on buildings. The results of the tests provide a specification of the concentration of the anion per volume [mg / l]. For evidence of salts these tests have proven themselves in practice. A statement about the specific salt that is present cannot be given, because of the incomplete information regarding the associated cation to be given.

Preliminary Results- Water Temple

The Water Temple is spring sanctuary in the city of Zaghouan located at the foot of the mountain range Djebel Zaghouan. The building is located in a park area with several archaeological structures. Only a section of the structure was selected for the conservation-scientific study. It concerns the interior and exterior of the cella and the first two fields in the east and west wing of the Water Temple. The floor area was not investigated, but the vault zone certainly.

Inventory- Building and Restoration Materials

Lime stone ashlar masonry

The appearance of the temple is determined by the large-sized ashlar masonry made of gray (-blue) limestone. This stone was extracted from directly neighbouring rocks of the mountain (Fig. 1 and 2). The material was used for the rising masonry, from the ground level up to the height of the capitals. The building material was employed for vertical sections, but not for vaults. The stone is dense and shows no macro-porosity. It has several inclusions, which do not follow a layering and show themselves in white and orange-red lines (Fig. 3 and 4). The chemical composition of the inclusions differs from the main material. The white lines could be quartz and the red coloured lines could be an indication for ferrous minerals. Another characteristic of the stone are small, longitudinal holes in the otherwise homogenous matrix, which can be mistakes for cracks. However, they are immanent in the rock and have no damage potential.

The surface processing of the limestone blocks is particularly noteworthy. Geometric patterns were created with fine decorative lines, using most probably pointed chisels (Fig. 5). In the interior and partially on the exterior walls of the cella, periodic holes and remains of a backfilling mortar can be observed in the ashlar masonry (Fig. 7). These findings can indicate at least a partial facing of the masonry with stone slabs (possibly marble). The light pinkish backfilling mortar can be interpreted as hydraulic lime mortar with various fine grained aggregates, including also ceramic materials.

With an exceedingly thin joint pattern, the masonry should probably appear as dry wall. Nevertheless, there are a large number of mortar remains from what was most likely the original mortar bed of the ashlar masonry. The mortar has a white matrix with aggregates of different stone fragments. It is a lime-bound system, possibly with hydraulic properties (Fig. 6).

In front of the cella architectural elements of decorative architecture from the entablature area of the Water Temple, such as architraves are stored. Those contain of a noticeable different limestone[1], with an even more homogenous matrix without any visible inclusions and a beige colour. Due to the colour and the homogenous characteristics it may have been selected for the decorative surface of the architecture.

Tufa-Limestone - vault zone

Above the ashlar masonry one finds a strongly deviating masonry. The **vault zone** consists of a rubble masonry with broad joints. The masonry stone is most likely a calcareous tufa (also called Sinter tuff, tufa-limestone). Due to its low weight, this highly porous limestone is very suitable for the construction of vaults (Fig. 8 and 9). The formats of the masonry stone vary greatly, depending on the function and placement in the structure. Partly they were worked in a rectangular form, partly they were used as rubble stones.

Due to a major restoration phase, covering nearly the entire joint inventory of the masonry with restoration mortar (see below) no statement about the original mortar of this type of masonry can be provided. Additionally, the great height of this type of inventory, without the possibility of close observation, allows only a superficial inspection. The original design of the visible surface of this masonry is only preserved in remains. The entire tufa masonry was probably covered with a layer of plaster (Fig. 10). The fine plaster was decoratively designed in sections (Fig. 11).

Rubble stone masonry cella

The eastern and the western wall of the cella show another masonry typ (Fig. 12). It was designed in the form of rubble stone masonry with a wide joint pattern. The stones were arranged in layers and partly brought into a rather rectangular shape. The masonry stone is mainly made of the nearby gray limestone same as the big ashlar masonry. The original mortar is hardly visible any more, since most of it is covered with modern restoration mortar. Nevertheless, in some areas the original mortar is visible, which consist of an orange matrix with aggregates of various stone fragments. The mortar has low strength and is lime-bound with probably hydraulic properties.

In the rain protected areas of the exterior rubble stone masonry of the cella walls, a joint coating has been preserved in sections, as well as a few remains of wall plaster (Fig. 13).

Previous restorations

The Water Temple has undergone at least one large-scale restoration phase. Several indications can be found on the entire structure. In the context of this report, only the cella and the first fields of the wings will be discussed. In comparison to historic photographs from 1974[2] one can observe, that in the vault zone as well as in the rubble walls from the cella missing parts

[1] Rakob describes in his articles, that the stone is a sandstone (Rakob 1969 and 1974). The chemical tests performed during this investiagation shows a different result, the blocks being made of limestone (Laboratory investigations could provide more accurate results).

[2] Published article from F. Rakob, Das Quellenheiligtum in Zaghouan und die römische Wasserleitung nach Karthago, Mitteilungen des DAI, Römische Abteilung, Band 81, Mainz 1974.

were closed in the last 47 years. The new masonry blocks were adapted to the original masonry in material and shape (Fig. 14). The supplemented areas in the rubble stone masonry of the cella were made of a slightly different stone. This has a lighter colour and also a more rectangular shape. Thus, restored and original wall sections can be distinguished via close observation. In the vault zone, no exact statement can be made due to the superficial examination from the ground. Additionally, the joints in this rubble stone walls of the cella walls and the vault zone were closed with at least two different restoration mortars (Fig. 15). All restoration mortars can be interpreted as fine-grained hydraulic lime mortar with probably cement added as binding agent.

The chronological classification of these interventions is difficult to determine. A verbal information by the INP indicates a restoration in the 1980/90s. The reports and/or images of these interventions are still being researched by the colleagues of the INP and will enrich the clarification of the chronology of the building with the modern phases.

Most common deterioration patterns

Crusts and Deposits

The surface of the object is covered with various deposits and crusts. This covering of the stone surface and wall structures occurs more frequently in areas protected from the rain.

The first type of crust to be observed has an orange colour and is very similar to the oxalate patina found on ancient buildings throughout the Mediterranean region (Fig. 16). It is distributed in large areas in the east and west wing as well as in the interior and exterior space of the ashlar masonry. There is no potential for damage originating from this crust in the case of this object. On the contrary, the thin layer acts as protection layer for the substance underneath.

Furthermore, in large areas in the east and west wing as well as in the interior and exterior of the ashlar masonry of the cella white deposits on the vertical stone surface can be observed (Fig. 17). This very soft and calcareous crust can be found below the restored tufa areas, increasingly in rain-protected areas. The origin of the deposit is ambiguous; it might be a leached binding agent (lime) from the restoration mortar above.

The last type of crust was found on the two outside rubble walls of the cella in the rain protected area along the south corners. The original joint coating has been preserved in this area. On top of that inventory a partially black crust as superficial layer is to be observed (Fig. 18) This could be soiling or gypsum crust. No damage potential can be observed from this crust either.

In summary, it can be stated that the deposits and crusts observed on the stone and masonry surface on the selected building section have no harmful influence on the substrate, if at all, only represent an aesthetic impairment. Material-scientific analyses from samples in the laboratory would be necessary for a more precise identification in all three types of crusts / deposits.

Scaling

Scaling means the "Detachment of stone as a scale or a stack of scales, not following any stone structure and detaching like fish scales or parallel to the stone surface. The thickness of a scale is generally of millimetric to centimetric scale, and is negligeable compared to its surface dimension."[3] At the Water Temple this damage pattern occurs specifically at the surface of the gray limestone (Fig. 19). Especially the valuable decorated stone surface gets lost on a large scale due to this damage.

Fragmentation

Fragmentation is defined as "The complete or partial breaking up of a stone, into portions of variable dimensions that are irregular in form, thickness and volume"[4]. In the case of the gray limestone the pattern fragmentation is part of its natural decay (Fig. 20). These phenomena occur on large areas of the object and is connected with major loss of substance.

Lichen / Moss / Black Biofilm and Plants

The biological colonization on mineral materials in the exterior is common. At the Water Temple one can observe typical microbiology for the Mediterranean Region. The Lichens are found on all surfaces of the monument, however, a very severe growth, can be seen on the top of the vault, so that almost the entire surface is covered with lichen and hardly any surface of the object is visible. Mainly the white crust lichen is found (Fig. 21). The other two lichen genera show an orange to yellow colour and a black to blue colour and are less common on the object. Very rarely mosses are seen, which grow in areas of longer and higher water occurrence.

The colonization of cyanobacteria, bacteria, fungi and lichens form a black biofilm, which is characteristic of the Mediterranean area in general (Fig. 22). The characteristic black surface of the object, whether rubble wall or gray ashlar blocks, is an indication of the presence of black biofilm.

Occasionally also plants are to be observed in the examined area. These are increasingly attracted by weak areas, especially joints, cavities and cracks, in order to grow (Fig. 23).

Salts

In order to clarify the potential contamination of the building structures by harmful salts, salt tests were carried out. Investigated were only areas with white deposits (maybe salt efflorescence) or damaged surfaces. In summary, the tests show that the structure does contain salts that are harmful to the building. Nitrates and Chlorites were detected. Nitrates origin from biological substances from animals and humans. Chloride could be salts present in the ground on which the building stands. But they can also be present in the building or restoration material itself, for example cements, depending on their manufacture.

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[3] ICOMOS-ISCS, p. 26 f.

[4] ICOMOS-ISCS, p. 22 f.

It is interesting to note that salts were still detected at heights of several meters. It is possible that salts transported in the water can be found at these heights. However, it is also an explanation that the object is also accessible from above for animals and humans. The salts introduced by their activities could have thus also penetrated from above. Unfortunately, it must also be observed that damage caused by crystallization cycles of the salt occurs in the historic materials and not in the restoration materials.

Cracks

The blocks of the ashlar masonry are primarily affected by this damage pattern (Fig. 26). On the one hand, these are rock-imbedded crack systems of the stone, and also part of the specific weathering phenomenon of fragmentation (see above). In addition, there are also individual cracks in the stone structure to be found. The vertical crack in the architrave/door lintel above the entrance to the cella may indicate a static problem in the cella's vault zone (Fig. 27). The reason for this could be the missing architrave / lintel below the cracked block, meaning the load of the roof above lies in this area only on one instead of two stone blocks as constructed. This condition should be examined by a structural engineer, as there is a particularly high number of visitors in the cella.

Glossy aspect

The stone surface appears in the affected areas changed, defined as follows: "Aspect of a surface that reflects totally or partially the light. The surface has a mirror-like appearance."[5] The cause of this alteration of the surface is the countless contact of the stone surface by visitors. Either when climbing on the ruins or touching with hands or shoes. The affected areas also show discoloration, the light gray stone is heavily darkened to a dark gray colour (Fig. 28). At the selected study area of the Water Temple glossy surfaces can be found on the cella walls and structures to about 2 m height.

Graffiti

At the investigated area many Graffiti's can be overserved at the ashlar masonry as well as on the rubble stone walls (Fig. 29). This damage pattern is defined as „Engraving, scratching, cutting or application of paint, ink or similar matter on the stone "[6].

Missing masonry and missing / damaged joint mortar

Missing masonry manifests in missing areas in the masonry, with masonry stones as well as joint mortar lost completely (Fig. 30). In contrast, there are also areas with intact masonry stones, whereby, the joint mortar is completely lost or damaged severely (Fig. 31). Since a large part of the rubble stone masonry has been restored, this damages rarely occur in this type of inventory. In the ashlar masonry a lot of the joint mortar is missing.

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[5] ICOMOS-ISCS, p. 54 f.

[6] ICOMOS-ISCS, p. 56 f.

Causes of damages and evaluation of state of preservation

In the examined area of the Water Temple, the most frequently occurring damage patterns can be attributed to two causes. The first damage cause is natural degradation due to weathering from direct exposure to the climate and natural decay of the gray limestone. The natural deterioration of this stone is indicated by cracks, fragmentation and scaling. The natural weathering caused by climatic conditions, such as strong solar radiation in summer and heavy rainfall in the rainy seasons, favours damage such as biological colonization.

The other cause of the damage is related to the anthropogenic utilization of the ruined site. The fact that the monument is visited by the public is in general very encouraging. It means that the monument has an important social value. The area is visited for leisure activities and also within the framework of training courses and school trips. A negative aspect is that visitors climb onto the ruins and can thus break off substance in addition to producing glossy surface. Especially problematic for the safety of visitors is access to the vault zone of the Water Temple (Fig. 32). There are no barriers in this area, and the static load-bearing capacity of these ruinously preserved sections of the building should be examined. In addition, graffiti are strongly discouraged in this historical context on the valuable surface.

In principle, the investigated areas can be classified in a medium state of preservation. Acute loss of substance was not observed, but conservation efforts should be made to minimize damage. In particular, it should be noted that a structural examination of the crack in the architrave / lintel above the entrance should be carried out. Furthermore, an improvement of the safety of the visitors should be discussed. Conservation measures to reduce the loss of substance, especially in the limestone masonry, is recommended. The restored areas of the rubble stone masonry are still in good condition. Nevertheless, a monitoring concept should be developed and maintenance measures should be implemented.

Preliminary Results- Aqueduct, Oued Miliane Valley, 12 Pillars

A section of the aqueduct in the Oued Miliane Valley was selected for the investigation during this working campaign. It contains well preserved aqueduct pillars from several phases of construction from antiquity to recent restorations. The selected section consists of 12 pillars and 11 fields, which represent the connecting arches between the individual pillars. The section runs north-south in this area next to the main road between Zaghouan and Tunis. In the course of the campaign, work numbers were assigned to the individual piers and fields. Thus, the identification begins with pillar no. 1 in the south to pillar no. 12 as northern end. Between pillars no. 1 and 2 is the field 1-2 and so on until the last field 11-12.
Due to the height of the structure, a detailed investigation could only be carried out in the first 2 m of the elaborated architecture. Above this area, a coarse survey was carried out. No information can be given about the specus zone at the present time.

Inventory- Building and Restoration Materials

Roman Ashlar Masonry (Opus quadratum)

Roman construction phases are still found in the examined section of the aqueduct. These are characterized by large-format ashlar masonry with a thin joint pattern (Fig. 33). The masonry stone consists of a fine-grained porous sandstone (quartz-arenite) of Tunisian origin (Fig. 34). It has a homogeneous and highly porous matrix with white inclusions in the shape of thin veins. The lithification of the stone is mainly produced by mechanical and chemical compactation and has not been cemented[7].
Mortar remains of the original joint mortar can also be found, which can be interpreted as hydraulic-limemortar characterised by white binding agent and aggregates of various stone fragments.
The internal structure of the Roman aqueduct pillars and arches could not be seen at the investigated section, but could be inspected at other sections. It demonstrates an opus caementicium core, which is clad with one to two layers of sandstone ashlar blocks.
This type of inventory can be observed from pillar no. 1 to no. 3.

Roman Arch- (Opus caementicium type I)

Not observed in the selected section in situ, because of limited access, just partially preserved on the ground, one can find opus caementicium fragments, collapsed from the arch and specus

[7] Petrophysical characterization of the sandstones has been carried by K. Zaghlami, Las Areniscas Miocenicas de la formacion fortuna utilizadas en la construccion del acueducto romano de Zaghouan-Carthago (Barcelona 2003)

area of the building (Fig. 44). The structure of the opus caementicium was originally covered with a sandstone masonry at the east and west facade, as can be seen in Fields 1-2 and 2-3 (Fig. 35). The underside of the arches was not covered with stones, but the cast vaulting was most likely plastered. This original surface of the vault soffit is rarely preserved, presumably at Field 1-2 and 2-3 (Fig. 36).

One of those opus caementicium fragments on the ground was investigated, so the material can be described as follows (Fig. 45): The stones in the mortar matrix are mainly sandstones, although others such as limestones occur occasionally. They have a size of about 8 to 17 cm and can be interpreted as rubble stone. The mortar is white, porous and has a high strength. In the matrix lime lumps with a size of up to 1 cm were detected. Together with the hydrochloric acid test, a lime mortar can be assumed, which has probably hydraulic properties. The aggregates of the mortar consist mainly of sandstone grains, but also other stone fragments and ceramic material. Whether the ceramic material has a hydraulic effect on the mortar cannot be determined in the context of the in situ investigation. The aggregates have a size of up to 1.5 cm. The smallest visible grain is 1 mm.

Supporting Wall (Ashlar masonry and opus caementicium type II)

On pillar no. 1 to no. 4 on the east side, one can find east-west oriented supporting walls (Fig. 41). The dating of this intervention still has to be confirmed. The building material consist of reused sandstone blocks as an outer construction filled with opus caemeticium (Fig. 42). The stones in the mortar matrix are limestones and sandstones of different varieties. They have a size of up to 30 cm and can be interpreted as rubble stones. The mortar of the opus caementicium can be described as hydraulic lime mortar with different aggregates. In the connection area between the opus caementcium and the ashlar masonry fine-grained mortar can be observed, most probably with the same binding agent as in the opus caementicium, only with finer aggregates. At certain intervals an approximately 2 cm thick interlayer of a different mortar can be observed. This layer correlates with the height in position of the sandstones blocks of the ashlar masonry. The mortar characterises itself with ceramic fragments as dominating aggregate type.

Remark: Specus

During this campaign it was not feasible to examine the specus in the selected section of the aqueduct (Fig. 43). A survey of an accessible specus section in the north of the Oued Miliane Valley was nevertheless conducted. The preliminary information from this survey will be briefly summarized. The wall and vault of the roofed specus were constructed in the technique of opus incertum. In the surveyed section, both Roman and medieval layers are preserved in the mortar bed of the specus. On the specus floor, seven different layers of various mortars could be detected. On the vertical wall, a mortar layer and a sinter layer on top of it could be detected. The sinter layer is partially covered by up to four other mortar layers.

Rammed-earth construction (Pillars and Arches with Arch stones)

After partial destruction and decay of the roman aqueduct, the pillars including arch and specus were reconstructed and restored in a later construction phase using a completely different technique, namely that of the Pisé technique (Fig. 37). The material from which the rammed-earth inventory (Pisé), namely the pillars and most likely also the arch area and Specus were produced, can be described as follows. It demonstrates a porous lime and possibly mud bound matrix with low strength. The presence of lime was proven both by means of the hydrochloric acid test and by the existence of lime lumps with a size of up to 1.5 cm. The aggregates consist of white limestone, ceramic fragments, volcanic rock, sandstone grains and other not defined stone fragments. (orange, red, gray, etc.). The aggregate size varies from approx. 8 cm to 1 mm. The grain shapes observed are both slightly rounded and angular. Since the observation focused on the material near the surface, a different composition of the inner matrix of the pillars cannot be excluded.

Occasionally, the original surface of the rammed-earth structure can be observed (Fig. 39). It is characterized by a smooth surface and an accumulation of the binder as well as imprints of wooden boards of the cast. Especially on the east side of the structure in the arch zone this surface is assumed.

Due to manufacturing techniques, a thin interlayer was applied at intervals of about 80 centimetres between the individual rammed-earth sections. This horizontal layer is found in most cases above the putlog holes of the wooden cast (Fig. 37). It consists mainly of lime with occasional mineral aggregates.

Not observed on the studied sections, but on other Pisé pillars in the Oued Miliane Valley, traces of surface decoration could be found. These are superficial white vertical strips between the horizontal white interlayers. A first hypothesis suspects the imitation of an ashlar masonry.

The arches of the rammed-earth inventory category were also built using the same Pisé technique, with one difference – the vault was executed with arch stones (Fig. 40). They are made of sandstone masonry. The joint mortar has a similarity with the interlayer of the rammed-earth sections. Therefore, it can be assumed that it is a lime mortar.

The inventory of the rammed-earth construction could be detected on pillar no. 4 to no. 12.

Previous restoration interventions

A number of restoration interventions were observed on the studied section and are presented in summarized form in the following paragraphs.

An extensive restoration of some pillars and arches was carried out with the construction of a new masonry (Fig. 46). Whether this is only a facing masonry or the entire structure was constructed with the masonry cannot be clarified in the context of this on-site investigation. The formats of the ashlars are smaller than those of the original Roman masonry. The stones are made of sandstone, probably from the same source than the roman elements. Characteristically appears the joint pattern of this treatment. The joint mortar probably protrudes several centimetres beyond the actual joint width, resulting in an optically very wide joint pattern. The joints and the masonry block are at the same level. A so-called joint line was drawn in the middle of the respective horizontal and vertical joints. The mortar appears in an orange-white surface with a white-grey matrix. Due to the high strength, the mortar can be characterized as hydraulic mortar and an addition of cement in the binder is suspected. The grain size of the aggregates differ from 1 to 4 mm and consist of a variety of mineral fragments. This type of inventory can be found on pillar no. 1 to no. 3, mainly on the west side.

Special attention in the restoration of the building was given to the base zone of the rammed-earth pillars. The large voids in that area were closed with mortar as a substructure and plaster as a top layer (Fig. 47). The plaster characterises as thin layer of dense, brown fine grained plaster with high strength. The aggregate consists mainly of silicates and carbonate minerals with sizes from 1 mm to 1.5 cm. The mortar underneath the plaster layer consist of the matrix itself and distributed lime stones from 2 to 12 cm. The mortar matrix itself has a gray to brown colour an aggregates from 1 mm to 1.5 cm. This restoration intervention could be observed mainly on pillar no. 4 to no. 11.

In the arch zone of the building restoration interventions with brown to gray plaster was conducted (Fig. 48). In specific, damaged areas of the rammed-earth structures were closed with this material. A more detailed description cannot be given due to the great distance to the material during the work on-site. This intervention can be observed nearly in the whole arch and specus area of the building, except from pillar no. 4 to 7 on the west side and pillar no. 1 to 3 on the east side.

The restoration of pillar no. 12 is unique and distinguishes itself from all other pillars in this section. In this case, the entire surface of the pier was covered with reinforced concrete as a substructure and a brown plaster as exposed surface (Fig. 49). The dimension of the pier has become larger due to this measure.

Most common deterioration patterns

Due to the huge building structure and no possibility to observe the higher surface of the objects (above 2 m) in detail as well as the timeframe it was decided to reduce the mapping of the condition to very coarse categories.

Crusts and Deposits

At the object surface crusts and deposits could be overserved (Fig. 50). These occur mainly in the upper areas of the structure; hence a precise characterization cannot be provided. Nevertheless, it can be assumed that these crusts/deposits are related to the use of the structure as a water pipeline. The deposits have a similar appearance to a lime crusts due to water leakage. Therefore, it is assumed that at some point in the history of the building, when water was still circulating in the specus, leakages in particular areas occurred. The water ran down over the surface for a longer period of time and it formed lime crusts.

Cracks

The structure of the building has a large number of cracks in all areas. Mainly single cracks or characteristic vertical crack systems in the rammed-earth structure can be observed.
Single cracks in the ashlar masonry run sometimes only within one ashlar block. However, in some cases they also run across several blocks. Cracks can also be seen at the boundaries between two different building materials (Fig. 51).
A prominent crack system can be observed in the rammed-earth pillars. Here, the cracks run vertically across one or more rammed-earth sections. Approximately two to three of these cracks can be seen each side. The cause of these cracks in the Pisé inventory could not be determined exactly. They could be shrinkage cracks or cracks caused by building structure movement.

Biological Colonization

The structure, which is exposed to weathering throughout the year, shows a large diversity of biological colonization (Fig. 52). All microorganisms and plants, which have already been described in the section on the water temple, can also be found on the aqueduct.
In particular, it should be noted that in the arch and in the specus zone, large bushes and small trees are already growing in the heavily damaged rammed-earth inventory. These have a great potential for damage due to root growth within the structure.
Furthermore, especially the west side of the structure is heavily overgrown with black biofilm and lichens. It can be assumed that the west side is the façade that is most exposed to rain.

Salts

In order to clarify the potential contamination of the building structures by harmful salts, chemical tests were carried out. Investigated were only areas with white deposits (maybe salt efflorescence) or damaged surfaces. In summary, the tests show that the structure does contain salts that are harmful to the building. Nitrates and Chlorites were detected. Nitrates origin from biological substances from animals and humans. Chlorides can originate from the building substance itself or restoration materials. They also could be transported in water rising from the soil. Damages in the base zone of the pillars could be attributed to the presence of salt and their damage potential next to other decay phenomena.

Missing parts

Missing parts can be observed in all areas of the structure. Due to the severe erosion of the sandstone, hardly any original surface is preserved (Fig. 53). The same must be noted for the Pisé surface. A different rate of weathering can be observed between the interlayer and the rammed-earth material (Fig. 54). Direct weathering causes loss of substance of the valuable surface of both main building materials.
Furthermore, the rammed-earth base zone is massively affected by loss of substance. It has to be stated that the restoration mortar and restoration plaster are too hard for the soft original building material, which results in damages in the rammed-earth substance.

Causes of damages and evaluation of state of preservation

The selected section of the aqueduct presents itself in a ruinous state with no utilization at the moment. The causes of damages can be attributed mainly to natural decay phenomena of the building material. Next to statically precarious cracks, the lost surface on nearly the entire building section is to be noted. The exposure of the building materials sandstone and rammed-earth to weathering over the centuries is the reason for this valuable loss of substance. The extent to which the salts are harmful to the building structure, caused by anthropogenic use (passing herds of sheep and goats) cannot be fully clarified after the on-site investigation. The improper restoration of the base zone, through the use of unsuitable materials, has to be reported unfortunately. The degree of damage in the arch and specus zone could not be determined in detail, as it was not possible to carry out an assessment during this campaign.

In general, this section has to be classified in a poor state of preservation. The reasons are the damages listed above, which contribute to the steady loss of substance. Hence conservation action is recommended. In particular, it should be noted that a structural examination of the entire structure should be carried out. Conservation measures to reduce the loss of substance, especially in the rammed-earth inventory has to be carefully planned and suitable restoration materials need to be applied for this sensitive material. Moreover, the development of a monitoring concept and the implementation of maintenance measures are recommended.
It would be desirable to define a common restoration goal for the entire section in the Oued Miliane valley and to unify the heterogeneous appearance by means of restoration measures.

Conclusion

The accomplished tasks and preliminary results present a major step to gain the necessary data, to form a concept for preservation of the section of the Aqueduct and the Cella of the Water Temple in regard to the whole context of the hydraulic complex. The final results of this project will additionally contribute to the nomination process as UNESCO World Heritage Site of the Zaghouan-Carthage hydraulic complex.

Figures


Fig. 1: Rock of Mountain, nearby the Water Temple
Fig. 2: Rock of Mountain, inside the Water Temple, West of the Cella

Fig. 3: Inclusions in gray limestone, red line, Water Temple
Fig. 4: Inclusions in gray limestone, white lines, Water Temple


Fig. 5: Stonemasonry processing of gray limestone, fine geometrical lines, Water Temple
Fig. 6: Joint mortar of ashlar masonry, Water Temple


Fig. 7: Backfill mortar on ashlar masonry, cella, Water Temple
Fig. 8: Calcareous tufa, vault zone, Water Temple

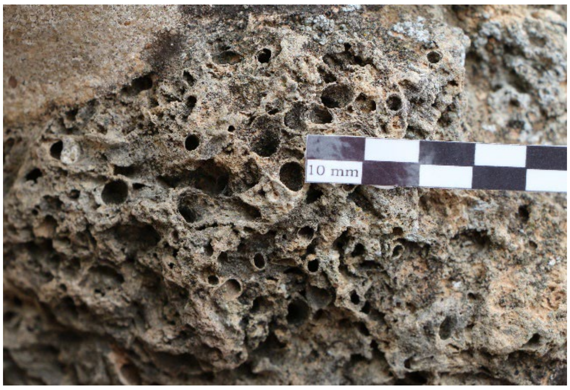


Fig. 9: Calcareous tufa detail, vault zone, Water Temple
Fig. 10: Residues of plaster, vault zone, interior cella, Water Temple



Fig. 11: Residues of decorative plaster, vault zone interior cella, Water Temple
Fig. 12: Rubble stone masonry, cella wall, Water Temple


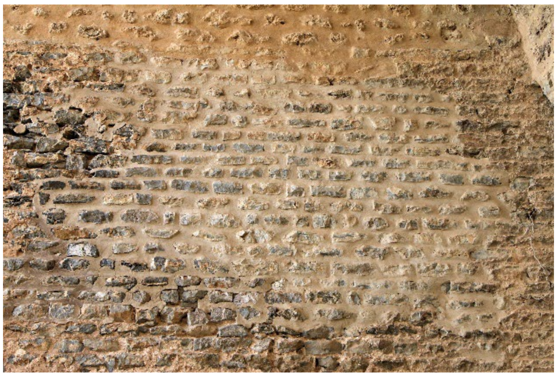
Fig. 13: Joint coating, cella wall, Water Temple
Fig. 14: Restoration interventions, new masonry, cella wall, Water Temple

Fig. 15: Restoration interventions, restoration mortar, vault zone, Water Temple
Fig. 16: Orange crust, ashlar masonry, wing, Water Temple

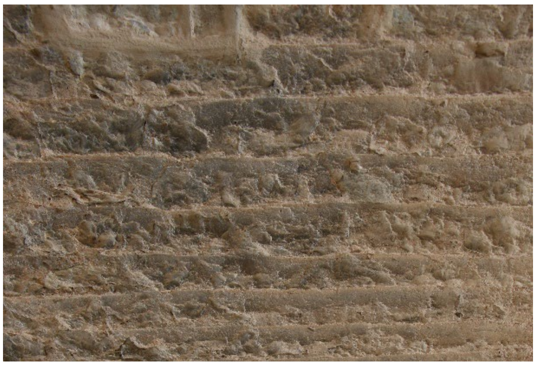

Fig. 17: White crust / deposit, ashlar masonry, wing, Water Temple
Fig. 18: Black deposit / crust, cella wall exterior, Water Temple

Fig. 19: Scaling, ashlar masonry, wing, Water Temple
Fig. 20: Fragmentation, ashlar masonry, wing, Water Temple

Fig. 21: Lichen, Water Temple
Fig. 22: Black biofilm, vault zone, Water Temple

 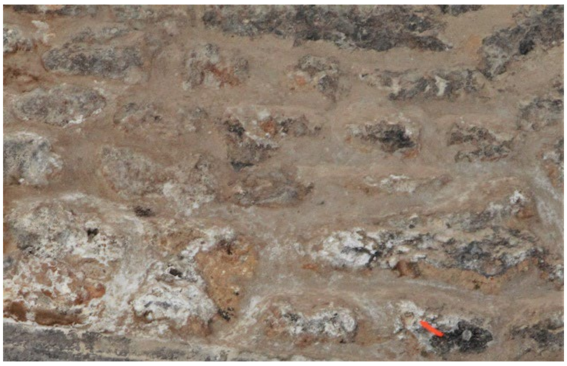

Fig. 23: Plants, ashlar masonry, cella exterior, Water Temple
Fig. 24: Salt efflorescence, rubble stone wall, vault zone, interior cella, Water Temple

 

Fig. 25: Damp spots, possibly due to salts presence, rubble stone wall, cella interior, Water Temple
Fig. 26: Cracks, ashlar masonry, cella entrance, Water Temple

 

Fig. 27: Vertical crack, architrave / door lintel, Water Temple
Fig. 28: Glossy aspect, cella interior, Water Temple

 

Fig. 29: Graffiti, roof cella exterior, Water Temple
Fig. 30: Missing masonry, rubble wall, exterior cella, Water Temple


Fig. 31: Missing joint mortar, ashlar masonry, Water Temple
Fig. 32: Visitors walk on vault zone, Water Temple


Fig. 33: Roman Ashlar masonry, middle part of wallstructure in this picture, Aqueduct
Fig. 34: Detail Sandstone, Aqueduct


Fig. 35: Roman arch, Aqueduct
Fig. 36: Most likely original surface (plaster) in vault soffit, Aqueduct

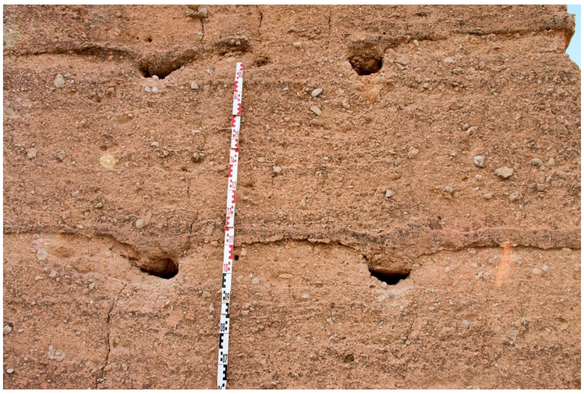


Fig. 37: Rammed-earth construction, Aqueduct
Fig. 38: Detail rammed-earth structure, putlog hole and interlayer (upperhalf of picture), Aqueduct


Fig. 39: Detail rammed-earth original surface preserved partially, Aqueduct
Fig. 40: Rammed-earth arch zone with sandstone masonry, Aqueduct


Fig. 41: Supporting walls, Aqueduct
Fig. 42: Supporting walls, opus caementicium core faced with sand stone ashlar blocks, Aqueduct


Fig. 43: Specus, Aqueduct
Fig. 44: Collapsed fragment of roman arch zone, opus caementicium core, Aqueduct


Fig. 45: Detail opus caementicium core, collapsed fragment, Aqueduct
Fig. 46: Restoration intervention, sand stone masonry with so-called joint lines, Aqueduct


Fig. 47: Restoration intervention base zone of rammed-earth inventory, brown plaster and underneath restoration mortar, Aqueduct
Fig. 48: Restoration intervention in rammed-earth inventory, arch and specus zone, Aqueduct

 

Fig. 49: Restoration intervention pillar no 12, reinforced concrete and brown plaster, Aqueduct
Fig. 50: Crusts / Deposits on rammed-earth arch and pillar, Aqueduct

 

Fig. 51: Cracks between sandstone arch stones and rubble vault, Aqueduct
Fig. 52: Biological Colonization arch and specus zone, plants as well as black biofilm and lichens, Aqueduct

 

Fig. 53: Missing surface due to erosion of sand stone ashlar blocks, Aqueduct
Fig. 54: Missing surface due to erosion of rammed-earth matrix, Aqueduct

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

Three Pillars Aqueduct, La Malga (Tunis)
and two sections of Cisterns, La Malga (Tunis)

Report of on-site conservation-scientific investigation

Barbara Rankl

March 2022

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Introduction

As part of the project "Investigating the Roman hydraulic complex between Zaghouan and Carthage (Tunisia)" the second campaign on site in Tunisia was carried out. The project is implemented through a cooperation between the Austrian Archaeological Institute (OeAI) at the Austrian Academy of Sciences (OeAW) and the National Heritage Institute (INP) of Tunisia and is funded by the Austrian Agency for Education and Internationalisation (OeAD). During the three-week stay from 6th until 27th March 2022, the executed tasks were the conservation-scientific inventory and condition survey of selected object sections. The chosen areas demonstrate three pillars (P) of the aqueduct running south of the cisterns in La Malga (Tunis) as well as two compartments of the cisterns themselves partly. The output of this report determines the basic components for the development of preservation concepts. The Austrian and Tunisian team members worked closely together in all steps. The investigations were carried out by B. Rankl (OeAI), K. Mighri (INP), and K. Dridi (INP) under the supervision of the project leaders Dr. G. Styhler-Aydin (OeAI) and Dr. H. Ben Romdhane (INP). The topics of building research and conservation science partially overlap, so the collaboration with I. Mayer (building researcher, OeAI) on site was extremely fruitful. The report is structured as follows. First, the methods implemented will be presented, and afterward, the preliminary results from the gathered data during the work on site will be explained. For detailed information on the building documentation and building research, see the internal report by I. Mayer.

Methods

For the conservation-scientific investigation of the inventory and condition of the building structures, already beforehand, a set of methods were discussed and selected. The methods implemented during the field campaign focused only on on-site inspection using non-destructive methods. Additionally, samples were taken for the laboratory investigation, to clarify detailed research questions.

Written and photographic documentation

First, a written inventory and condition description of the selected areas was carried out and placed in the context of the entire building structure. Photo documentation of all building materials, processing traces, and construction manufacturing details as well as the most common damage patterns were made. For the classification of damage patterns, the English-French version of the "Illustrated glossary on stone deterioration patterns" from ICOMS-ISCS was used.

Inventory and Condition Mapping

This established method in the context of preservation of monuments and building diagnostics provides comprehensive and clear information of the current situation found. Mapping is essential for the inventory and condition recording and demonstrates an indispensable

instrument in the context of planned and consequently executed restoration projects. It assists in the compilation of a treatment concept and the documentation of restoration measures as well as the condition assessment before and after the restoration. Additionally, samples taken and areas to be examined for on-site test procedures can also be precisely localized. Mapping is an important basis for monitoring.
At the beginning of the work on-site areas for mapping were determined. Mapping represents the graphic documentation of defined categories. Within the scope of this project, mapping was limited to the building material, damage patterns and localizing of on-site material-scientific tests as well as location of sampling. The defined categories always depend on the specific inventory and condition of the individual site. Each category is assigned a color. The basis plan is provided by Ortho-views of 3D laser scan data, which were produced by I. Mayer. For the spring campaign it was decided to choose only the Aqueduct La Malga in sections for mapping, the cisterns where excluded from this particular method due to time issues.

On-site material-scientific analyses

Next to the expertise of the stone conservator via optical and haptic investigation, on-site material-scientific analyses were carried out to support the overall diagnosis. The selected methods are non-destructive and easy to carry out on-site.
In order to support a general classification into the chemical composition of mineral materials, chemical analysis using hydrochloric acid (9% in water) is carried out. A drop of this liquid is placed on the surface to be examined. In the chemical reaction with lime, the liquid foams up. This is an indication that the material contains lime and this information can assist in determining materials such as stones, crusts and deposits.
The second method executed were salt tests. Salts, when infiltrating the structure of the building can cause damages, for example due to the crystallisation of the salt minerals. The presence of salts on the objects were verified with test strips. The areas or fragments to be examined were scratched off the surface with a scalpel and stored in a glass vessel which was filled up with water. After 10 to 30 minutes, the liquid with the possibly dissolved salt was examined using test strips. In the case of presence of salts, the test strips react with a color reaction. The investigation of the selected areas comprised a total of three different anions (Chloride, Sulphate, Nitrate), which occur most frequently in connection with harmful salts on buildings. The results of the tests provide a specification of the concentration of the anion per volume [mg / l]. For evidence of salts these tests have proven themselves in practice. A statement about the specific salt that is present cannot be given, because of the incomplete information regarding the associated cation to be given.

Preliminary Results- Aqueduct La Malga

The remains of the ancient aqueduct at the La Malga site are to be understood as the continuation of the aqueduct section in the Oued Miliane. The so-called La Malga Aqueduct is located in the district Carthage of the modern city Tunis. It runs from the east to the west, south of the La Malga Cisterns. The surrounding is created as a recreation area, without any entrance fee or fence. Additionally, it demonstrates an area for sheep and goat herds. Only a section of the structure was chosen for the conservation-scientific study. It concerns pillars in the west end of the park, with the numbers 26 until 28[1], north to modern concrete stairs.

Inventory- Building and Restoration Materials

The investigated section consists of antique building structures, zones of re-use as well as restoration and reconstruction interventions. Below the observed materials of the inventory of the monument section are described.

Roman

The antique structures are constructed from an opus caementitium core, covered with a slightly layered rubble stonewall[2] (Fig. 1). The masonry stones of the structure consist mainly of fine to middle-grained sandstones and lime-sandstones (Fig. 2). The mortar is most likely a hydraulic lime mortar. Large lime lumps can be observed in the binding media, with a size of up to 2 cm. The aggregates are made of various rock fragments. Noticeable are black subrounded rock fragments up to 2 mm and frequently brown subrounded rock fragments up to 1 cm in size (Fig. 3)[3]. In the investigated section this inventory can be found at P 28, in the collapsed field (F) 27-28, and in parts in the P 27 and 26.
It should be noted that the original surface of the masonry may be partially visible. It is characterized by a smoother surface and horizontal lines pressed into the mass with a tool. These structures can be observed on P 27.
In the arches of the aqueduct, one can identify antique big angular arch stones with slightly pointed shapes on the south side of the monument. Above the vault zone of both sides of the monument a horizontal layer with the same building material can be seen[4]. It marks a recessed edge / boarder to the specus wall (Fig. 4). The selected stone has a gray appearance, resulting from weathering and biological colonization. Actually, it has a light brown to beige color. It demonstrates a lime-sandstone with grain sizes from 250 to 500 micrometers. The stone has a very homogeneous structure, tending to delamination. It can be characterized by high porosity

[1] Within the project, a temporary numbering was assigned to the pillars and fields, in the same system as in the Oued Meliane. Pillar number 1 starts in the east end of the park, near compartment number 1 of the cistern, and runs up to pillar number 28 at the west.
[2] See mapping: Opus caementitium.
[3] For closer identification of the mortar samples were taken in order to carry out microscopic investigations. See Appendix, sampling protocol ZAQ_CAR_1.
[4] See mapping: Lime-sandstone blocks.

and low hardness. In the investigated section this inventory can be observed in remains in the collapsed arch and in the spandrel above P 26, 27 and 28 on the south side. On the north side one can observe this material in the horizontal layer below the specus in the spandrel of P 27 and 28.

The specus of the Aqueduct consists of two parallel vertical walls, covered by a vault. In the studied section, the walls are preserved in remains, whereas the roofing is not preserved.

Similar to the rest of the structure, the masonry consists of opus caementitium with slightly layered rubble stones on the visible surface (Fig. 5). The building materials, masonry stones and mortar, are very similar to those described above, namely sandstones and lime-sandstones connected with hydraulic lime mortar[5].

Noteworthy is the partially preserved coating with mortar / plaster to seal the specus[6]. Above it lies the remains of sintered crusts from the use of the aqueduct as a water pipeline (Fig. 6)[7].

In the investigated section the coating mortar / plaster consists of various layers. On the specus floor one can find a mortar characterized by big ceramic fragments, which has a layer thickness up to 4,5 cm. It is a hydraulic lime mortar with ceramic aggregates, with a size up to 3 cm and an angular shape. Most of them are around 1,5 cm in size. Sporadically other aggregates of mineral fragments up to 4 cm in subangular and subrounded shape and in gray, brown and black color can be traced. The binding media has a white color, which can indicate the absence of brick dust as an additive, nevertheless, the mortar has highly hydraulic characteristics.

On the specus wall another mortar was attached, using manifestly smaller ceramic fragments, but still can be described as a hydraulic lime mortar. Visible are small lime lumps scattered in the mortar with up to 2 mm dimensions. The binding media has a light pinkish color, which can indicate the presence of brick dust as hydraulic additive. The layer thickness is between 1,8 and 2,5 cm, the ceramic aggregates have an angular shape and sizes from below 1 mm to 2 cm. Additionally, calcareous and not calcareous stone fragments (different stones- mainly gray and white) were added as aggregates (Fig. 7).

In both lower corners of the specus wall and floor a thick bulge was applied, using a mortar with a very similar composition as the specus floor mortar.

As last layer, a fine gray mortar / plaster, with a smooth surface was applied on the wall as well as the floor of the specus (Fig. 7). On the wall, it has a layer thickness varying from 0,9-1,5 cm and on the specus floor it is 1,9-2,8 cm thick. It can be described as hydraulic lime mortar with calcareous and not calcareous stone fragments (different stones- mainly gray and white) as aggregates with subrounded and subangular shapes and sizes from below 1 mm to 3 mm, without any addition of ceramic fragments.

The calcareous sinter crust originate from the water running through the specus, when the building was in use as a hydraulic water system. On the floor of the specus very thin and dense

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[5] For closer identification of the mortar constructing the specus walls and for comparison with the mortar for the construction of the lower part of the building a sample of the mortar of the specus walls was taken. See Appendix, sampling protocol ZAQ_CAR_2.

[6] See mapping: Specus mortar

[7] See mapping: Sinter / Crust specus

layers of the crust, with a total layer thickness up to 2 cm can be seen. Contrarily the wall of the specus shows a different appearance from the calcareous sinter crust. Here one can observe very porous and thick layers of the crust with a total layer thickness of up to 12 cm. On the vertical wall the crust is preserved up to a level of 60 cm, which could correspond with the water level in ancient times.

Comment "Mortar with ceramic fragments"

A very distinctive material was detected on the wall surface of the spandrels above P 27 and 28. On the surface of the opus caementitium core one can observe a mortar-like layer with large ceramic fragments inside (Fig. 8). Whether this is an additional mortar layer or subsequently consolidated cultural debris can hopefully be determined by the examination of the sample ZAQ_CAR_3[8] taken from this material.

Re-Use

The object surface shows residues of materials, which can be traced back to later use of the building structures. According to oral reports, houses of the local population using the ancient structures as part of their buildings, e.g. walls, pre-existed at the site. These were removed at a currently unknown time[9]. The remains of the buildings mainly consist of residues of mortar layers and paint layers (Fig. 9)[10]. But one can observe also adaptations of the wall structure itself, such as a small niche, which could originate from the phase of re-use. Especially on the north side of the investigated section west of F 26-27 those residues were found.

Restoration and Reconstruction

The aqueduct in La Malga has undergone at least one large-scale restoration and reconstruction phase[11]. Prominent indications can be found on the entire structure on all sides of the aqueduct. In the context of this report, only the selected section will be described[12].
Starting on the top view of the aqueduct, one can find a large-scale flat concrete surface (Fig. 10). The original remains of the specus protrude from this measure. On the north side of the monument starting at P 27 and proceeding into the east a major reconstruction of the wall and vaulting structures of the inventory was executed. The original surface is not or just occasionally perceived. The execution of the reconstructions of arches and spandrels on the north side demonstrates a vertical facade without gradations (Fig. 11). An interpretation of the

[8] See Appendix, sampling protocol ZAQ_CAR_3.
[9] The Tunisian colleagues K. Dridi and K. Mighri are going to conduct archive studies, to clarify the re-use phase of the site.
[10] See mapping: Modern mortar and paint
[11] The Tunisian colleagues K. Dridi and K. Mighri are going to conduct archive studies, to clarify the interventions at the site.
[12] See mapping: Modern restoration type I.

dimension of this intervention, reckoning how much was reconstructed, can only be made by comparison with old photographs or the documentation of these measures.

The added materials consist of various stone blocks in angular shapes and different sizes adapted to their use as arch stone or masonry stone. The building material consists mainly of sandstones and lime-sandstones, but also other not closer identified stone varieties were observed. In some cases, re-used blocks (spolia) were detected within the reconstructed areas. The visible mortar can be described as hydraulic lime mortar, possibly with cement added to the mixture. The color on the surface is beige and brown to gray and the matrix is homogenous and porous. The aggregates consist mainly of sandstone grains up to 1 mm and various other stone fragments up to 1 cm in a subangular shape. For the execution of joint-sealing, the same level as the stones was chosen (Fig. 12).

The restoration and reconstruction of the south side of the monument have a slightly different appearance (Fig. 13). In the spandrels above the pillars, the original structures are still visible in contrast to the north side. On this side it was decided, to not fully reconstruct the shape of the monument, but always only the fields, starting with F 26-27. This means that the vault was reconstructed as well as the areas of the wall above the fields until the specus level. The original construction is preserved in the spandrel of P 26, 27 and 28. One can notice that there are at least two recessed edges / boarders in spandrels and arches. These were tried to imitate in the reconstructed areas. The accuracy of these reconstructed areas cannot be ascertained in parts. The execution and materials used for the restoration and reconstruction of the south side can be described as coherent with the materials from the north side. The only noticeable difference is that the joints are slightly below the level of the stones. Either this has already been executed or the joints are already slightly weathered back on this side.

The underside of the vault from F 26 to 27 was also reconstructed. Here you can see the wooden formwork of the construction of the vault very well pressed into the mortar. The materials, stones and mortar, are presumably the same as on the reconstruction of the north and south sides (Fig. 14).

The now described measures were graphically documented in the mapping with the key modern restoration type I. On the north side, deviating reconstruction material was noted at one location. Here, hollow bricks and cement mortar were used (Fig. 15). The location of this intervention is shown in the mapping with restoration type II.

Most common deterioration patterns and damages

Damages roman wall

The surface of the roman opus caementitium structure, namely the slightly layered rubble stone wall shows severe damage patterns, which will be discussed shortly. The masonry stones themselves show damage patterns like erosion, sanding, and alveolization. Erosion leads to a smoothed surface of the stone surface. In the case of the masonry stones, a differential erosion can be observed, meaning the erosion "does not proceed at the same rate from one area of the stone to the other. As a result, the stone deteriorates irregularly"[13]. With the term alveolization one can understand the "formation, on the stone surface, of cavities (alveoles) which may be interconnected and may have variable shapes and sizes"[14]. It can originate from "differential weathering possibly due to inhomogeneities in physical or chemical properties of the stone"[15]. Another damage image that can be observed is sanding, meaning the detachment of single sand grains of the sandstones and lime-sandstones[16].

The combination of those damage patterns led to the hollowing out and removal of the material from a few grain layers to several centimeters. On some stones the loss demonstrates extreme form, that hardly any material of the individual masonry stone is preserved (Fig. 16 and Fig. 16a).

Next to the masonry stones, the joint mortar is in very bad condition. It has weak properties with low hardness and shows sanding. In most of the cases, the joint mortar is not preserved in the first few centimeters. The problems in the masonry stones and the joint mortar correlate to each other and exponentiate the damage extend of the whole wall structure.

In the graphic documentation of the condition of the roman wall structures, it was decided to link all damage patterns from the masonry stones and the joint mortar to one key in the legend, named "Damages Wall"[17].

Biological colonization

The biological colonization of mineral materials in the exterior is common. At the aqueduct, one can observe typical microbiology for the Mediterranean Region. The lichens are found on all surfaces of the monument, however favorably on areas exposed to rain. In the case of the aqueduct, they appear in the specus area and on the north side of the monument. Yellow to orange lichens are especially common, but black and white lichens are also found on the surface (Fig. 17).

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[13] ICOMOS-ISCS, p. 30.
[14] ICOMOS-ISCS, p. 28.
[15] ICOMOS-ISCS, p. 28.
[16] See ICOMOS-ISCS, p. 20
[17] See mapping.

The colonization of cyanobacteria, bacteria, fungi and lichens form a black biofilm, which is characteristic of the Mediterranean area in general. The characteristic black surface can be mainly found on the north side of the monument.
Interestingly the north side of the specus wall inside is heavily colonized with black biofilm and yellow /orange lichens. The reason is, that here the structures tend to stay damp for a longer period of time as on other areas of the monument.
Occasionally also plants are to be observed in the examined area. These are increasingly attracted by weak areas, especially joints, cavities and cracks, to grow. Root pressure can cause cracks in the structure and hence can lead to damage or loss of material (Fig. 18).

Salts

To clarify the potential contamination of the building structures by harmful salts, salt tests were carried out. Investigated were only areas with white deposits (maybe salt efflorescence) or damaged surfaces (Fig. 19). In summary, the tests show that the structure does contain salts that are harmful to the building. Nitrates, Chlorides and Sulphates were detected[18]. Nitrates originate from biological substances from animals and humans. Chloride could be salts present in the ground on which the building stands. But they can also be present in the building or restoration material itself, for example, types of cements, depending on their manufacture. Sulphates can be deposited on the rock by the atmosphere and bond with the mineral materials. Particularly high levels of nitrates and sulphates were detected, whereas Chloride seems to play a minor role.
Unfortunately, it had to be observed that damage caused by crystallization cycles of the salt occur in the roman as well as restoration material. In the affected areas the material is weakened and also sanding can be detected, which leads to loss of material.

Deposits and crusts

Object's surface is covered with various deposits and crusts. Loose deposits of soil and other debris are observed on the horizontal object surfaces. Particularly noteworthy is the deposition of sanded mortar and stone material on the horizontal surfaces and on the ground in front of the object, where damage patterns of the category "damages wall", which have been described above, occur on the vertical surface of the masonry.
Little to be observed is crusts on the object's surface. Only on the underside of the vault, black crusts are observed (Fig. 20). These could be gypsum crusts. However, these black deposits could also be soot, originating from campfire's in that spot.

Delamination

The damage pattern delamination occurs on one specific material, the lime-sandstone blocks used for constructing the roman vault and horizontal layer below the specus (Fig. 21). It

[18] See Appendix, table result salt tests

presents itself as a physical separation into several horizontal layers following the stone laminae. Those fine cracks run parallel to each other through the block[19].

Glossy aspect

The surface appears in the affected areas changed, defined as follows: "Aspect of a surface that reflects totally or partially the light. The surface has a mirror-like appearance."[20] The cause of this alteration of the surface is the countless contact of the surface by visitors. In the case of the aqueduct glossy surfaces can be observed on the floor of the specus, due to abrasion of the shoes of the visitors when walking in the specus[21].

Cracks

In the investigated section of the aqueduct this damage pattern plays a minor role. Very limited areas show cracks, except for one location (Fig. 22). On the north side of the aqueduct west of P 28, a vertical crack runs through the whole structure, possibly triggered by earth motions in this area[22].

Collapsed area

Significant damage can be seen in F 27 to 28. Here, the entire arch with the specus has collapsed (Fig. 23). The fragments lie on the ground between P 27 and 28[23]. The collapse of building sections represents irreversible damage, which is accompanied by the loss of a great deal of original material. The time of the collapse could not be determined within the framework of the on-site investigations. Also here the research in archives could perhaps bring clarification.

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[19] ICOMOS-ISCS, p. 18.
[20] ICOMOS-ISCS, p. 54 f.
[21] See mapping: Glossy aspect
[22] See mapping: Cracks
[23] See mapping: Collapsed area.

Causes of damages and evaluation of state of preservation

In the examined area of the aqueduct in La Malga, the most frequently occurring damage patterns can be attributed to two causes. The first damage cause is natural degradation due to weathering from direct exposure to the climate and natural decay. The natural deterioration of the main building materials lime-sandstone and sandstones shows itself mainly in delamination, sanding, and alveolization. The natural weathering caused by climatic conditions, such as strong solar radiation in summer and heavy rainfall in the rainy seasons, favors damage such as biological colonization.

The second cause of the damage is related to the anthropogenic utilization of the ruined site. The fact that the monument is visited by the public is in general very encouraging. It means that the monument has an important social value. The area is visited mainly for leisure activities and tourism. A negative aspect is that visitors climb onto the ruins and can thus break off substance in addition to producing a glossy surface. Moreover, the contamination with salts, especially from nitrates, and the damage caused by it, can be attributed to the current agricultural activities by animals as well as human residues.

In principle, the investigated area can be classified in a medium state of preservation. However, it is important to emphasize, that the situation is very heterogeneous in terms of condition. The recently reconstructed areas are in good condition, whereas the non-conserved areas are in very poor condition. Unfortunately, it must be noted that precisely the areas especially worth preserving, the roman structures were not conserved. Necessary interventions such as the consolidation of the severely weakened masonry stones and the restoration of an intact masonry structure were neglected. The imbalance between the two states of the reconstructed and original areas is accompanied by the risk that future damage will increasingly occur in the already weakened zones and thus even more loss of substance of the original inventory are likely to occur.

Preliminary Results- Cisterns, La Malga

The remains of the ancient cisterns at the La Malga site are located north of the aqueduct. At the current state of observation, no connection between the two water systems could be detected. Contrary to the aqueduct, supplied by spring water from the hinterland, according to the current state of knowledge, the water in the cisterns was collected from rainwater. The structure consists of 15 compartments (comp.) alongside and connected to each other, as well as a transverse compartment adjoining in the south. Surrounded by a border wall and fences, the area is not accessible to visitors. For the conservation-scientific study during the campaign in March only the southern end of comp. 12 and 13 were selected. However, a general inspection showed that the materials and recorded damages of the selected areas largely represent the entire monument. The two compartments investigated are covered with soil in the interior, up to the vaulted area. Exceptions are several meters deep and wide east-west oriented sondages in each compartment.

Inventory- Building and Restoration Materials

Vault masonry

The north-south running cistern structures were constructed using the opus caementitium technique. The lower vertical walls (separation walls between compartments) were built first, whereby the stones and mortar were filled into a mold. In the vault section, probably only the lower formwork was built and on it rubble stones, were masoned with mortar in a slightly layered arrangement so that a wide barrel vault was created.

For the vault masonry various rubble stones with a size of up to 16 cm were used. The stones are classified as lime-sandstones and sandstones (up to three varieties). The mortar can be described as hydraulic lime mortar, which is characterized by a gray color and occasionally lumps are found in the binding media. As aggregate, many different rock fragments (black, red, gray, orange, green) were used, with a maximum grain size up to 12 mm (Fig. 24 and 25). The southern end of the barrel vault was executed with arch stones. This inventory is preserved only very sporadically. The arch stones have a rectangular and slightly wedge-shaped form. The characteristic lime-sandstone used for this purpose is very porous and tends to delamination. The mortar used to join the stones is the same mortar used for the rest of the vault (Fig. 26).

Spandrel and Shield Walls

Remains of the southern shield walls are still preserved in comp. 12 and 13. These were executed as opus caementitium construction. The masonry stones are mainly sandstones and lime-sandstones and can be characterized as rubble stones, of a size up to 25 cm. The mortar

of the wall construction can be described as hydraulic lime mortar and has a characteristic light brown color. The aggregates have a size up to 1,5 cm and a subrounded shape. Different stone fragments (brown to orange) were used for the aggregates of the mixture (Fig. 27 and 28).
As far as the visual inspection allowed, it can be concluded that the technique and the building materials, masonry stones and mortar, of the spandrel walls between the individual compartments are the same as those used for the construction of the shield walls.

Facade masonry

In very few remains masonry structures placed in front of the south end of the cisterns are preserved, which may represent a façade. It shows a slightly layered rubble stone masonry (Fig. 29). Regarding the materials, the masonry stones show a high similarity with the rest of the building. The mortar has a gray to brown color and can be classified as hydraulic lime mortar. White particles of up to 1.5 cm could be detected in the binding media, this may be lime lumps. The aggregates consist of non-calcareous as well as calcareous stone fragments (green, white, black, etc.) in subrounded and subangular form. The largest grain is 2 cm and the smallest grain is less than 1 mm.

Plaster exterior

Residues of plaster on the exterior of the monument could be found sporadically in several places. Thus, remains of plaster can be observed in the drain channel between the two barrel vaults, but also on the barrel wall itself. The thickness of the layers varies between about 15 cm in the drain channel and about 5 cm on the upper part of the barrel wall. The material of the plaster seems to be the same throughout. It is a hydraulic lime mortar and the bindingmedia has a white color. The aggregates consist of ceramic fragments in angular form and a maximum size of 3 cm. In addition, other aggregates can be seen, namely different rock fragments (lime-sandstone, sandstone) in subangular form and brown to gray color. The plaster layer is covered with a very fine and white layer; this could be a coating layer (Fig. 30).

Plaster interior

Evidence of plastering on the interior (walls and vaults) indicates that the wall and vault were plastered. How far to the top could not be reconstructed due to missing findings. The plaster has a layer thickness of 2 cm and gray color. The aggregates are subrounded to subangular and consist of different stone types (black, brown, etc.). The grain size varies from less than 1 mm to 1.3 cm. In the binding media are lime lumps visible with a maximum size of 3 mm. The plaster is most probably a hydraulic lime plaster. The surface appears white and smooth. Whether it is a coating (maybe originates also from the phases of re-use, see below) or deposits could not be clarified during the visual inspection (Fig. 31).

Re-Use

According to old photographs and oral reports, the cisterns were used as houses for the local population. The later installations of those houses were removed at a currently unknown time[24]. It can be assumed that the building had, after use as a cistern, even several phases of re-use. Evidence of this re-use might be, preserved scratchings in the plaster. But one can observe also adaptations of the wall structure itself, such as small niches, which could originate from the phase of re-use.

Restoration and Reconstruction

Major and minor missing parts were completed as part of at least one intervention. Elements were also reconstructed, such as the oculi in the vault. The restoration/reconstruction was conducted by filling the missing parts with rubble stone masonry (Fig. 32). The stones can be distinguished as calcareous and non-calcareous different types of stones up to 20 cm in size. Partly even historical (probably Roman) mortar fragments were used as " masonry stones". The mortar most likely consisted of a cement mortar (possibly with lime as an additional binder). The visible mortar on the surface has a gray to brown color and is very hard with hardly any porosity. The aggregates have a size up to 2 mm and consist mainly of siliceous rock fragments. For the production of the additions, the rubble stones were presumably placed in a formwork with mortar. After setting, the formwork was removed. Either the surface was later on painted to integrate the color of the additions to the originals. Or a different colored finishing mortar was applied to the surface. The additions protrude a few centimeters from the surface of the vault in the interior (Fig. 33).

[24] The Tunesian colleagues K. Dridi and K. Mighri are going to conduct archive studies, to clarify the phase of re-use at the cisterns.

Damage assessment

No detailed mapping of the damages was carried out during the campaign. Only a visual inspection was executed by the author of the report and the Tunisian colleagues. Nevertheless, a brief description of the damages, an assessment of the causes of the damages, and an evaluation of the state of preservation can be undertaken for the southern end of comp. 12 and 13.

In the investigated section the most common damage patterns occurred as follows. The most obvious damage is missing parts. The character of a ruin is characterized by missing parts, and this is also the case with the cisterns. In the examined area, the almost completely missing south facade and the largely missing shield walls as well as large voids in the spandrel walls are to be emphasized.

Unfortunately, it must also be noted that the opus caementitium masonry in the exterior is very damaged in some areas. The masonry composite of masonry stones and joints is deteriorated and weakened. This can be observed especially in the lower areas. The sanding of the lime-sandstones and sandstones and the mortar is particularly severe. In addition, on some masonry stones alveolization is also observed (Fig. 34). Interestingly, the gray mortar of the vault is in better condition than the brown mortar of the shield walls and spandrel walls. Not quite as badly affected as are also the arch stones, but those tend to delamination. In the affected zones, occasional salt efflorescence's can be observed.

The same damage patterns as described for the exterior wall can also be found in the lower area of the vaults in the interior, also together with salt efflorescence.

Another damage pattern can be observed in the interior of the vault. Hard, thick and black crusts can be observed in the upper area of the vault (Fig. 35). Salt tests have shown that these are most likely gypsum crusts. These gypsum crusts are problematic compared to the less dense and very soft structure of the building material. Thus, the typical scaling can be seen, which demonstrates the detached crust from the substrate including stone material.

The remains of the plaster on the inside are partially detached from the opus caementitium wall. Salt efflorescence can also be observed in these areas. On the surface of the plaster are many deposits and/or crusts.

Also noteworthy are the sometimes very carelessly executed additions, using mortar with very high strength. This demonstrates the risk, that the damage phenomena happen increasingly in the original materials and not in the restored/reconstructed areas.

Biological colonization is also very frequently encountered. A distinction must be made between the interior and exterior. Algae and black biofilm are found inside (Fig. 36). In the outside area, black biofilm lichens and especially plants and bushes can be observed. These seek weakened zones in the structure for spreading and the roots of those plants can partly be seen in the inside of the vault. Plants and bushes cause considerable damage (Fig. 37). Unfortunately, it must be observed that, as mentioned above, the restored areas are not as heavily affected as the original material, which indicates that the used restoration materials is not adequate and thus promotes damage to the original structure.

In contrast, the intact plastered wall structures in the sondages are not as severe affected by these damage patterns now mentioned. This can be traced back to the underground condition and thus protection of the structures before the recently executed excavations. On the surface of the fine white plaster one can observe, many pictorial and written scratchings in the plasters (Fig. 38).

In the examined area of the cisterns in La Malga, the most frequently occurring damage patterns can be attributed to several causes. The first damage cause is natural degradation due to weathering from direct exposure to the climate and natural decay. The natural deterioration of the main building materials lime-sandstone and sandstones, shows itself mainly in delamination, sanding and alveolization. The natural weathering caused by climatic conditions, such as strong solar radiation in summer and heavy rainfall in the rainy seasons, favors damage such as biological colonization.
Another cause of damage is related to anthropogenic utilization in combination with natural causes. The extreme salt contamination of this structure can accelerate or even partially cause the damages described above. Salt tests were carried out to specify the origin of the contamination. The tests show that the structure does contain salts that are harmful to the building. Nitrates, Chlorides, and Sulphates were detected. Nitrates originate from biological substances from animals and humans. Chloride could be salts present in the ground on which the building stands. But they can also be present in the building or restoration material itself, for example, types of cement, depending on their manufacture. Sulphates can be deposited on the rock by the atmosphere and bond with the mineral materials. Particularly high levels of nitrates and sulphates were detected, whereas Chloride seems to play a minor role.
In principle, the investigated area can be classified in a medium to poor state of preservation. However, it is important to emphasize, that the situation is very heterogeneous in terms of condition. The recently reconstructed areas are in good condition, whereas the non-conserved areas are in very poor condition. Necessary interventions such as the consolidation of the severely weakened masonry stones were neglected and are recommended to complete.

Conclusion

The accomplished tasks and preliminary results present a major step to gaining the necessary data, to form a concept for the preservation of the aqueduct and the cisterns at the La Malga site in Tunis. At both sites, conservation treatments are recommended, which should be followed by regular monitoring and maintenance measures. The results of the material-scientific studies in the laboratory of the samples taken will contribute to a more precise characterization and comparison of the materials, thus enriching the preliminary results. The final results of this project will additionally contribute to the nomination process as UNESCO World Heritage Site of the Zaghouan-Carthage hydraulic complex.

Figures

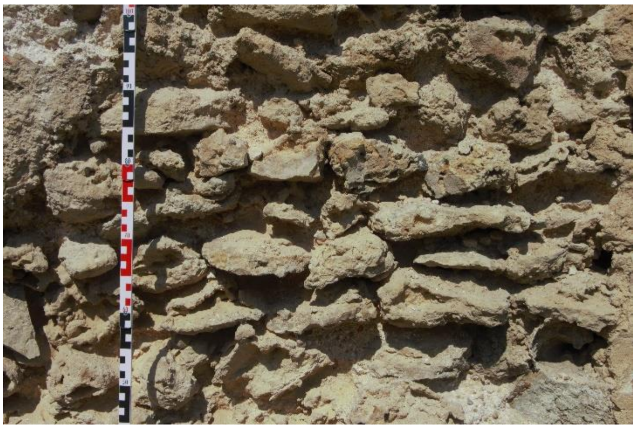

Fig. 1: roman inventory, opus caemetitium core with slightly layered rubble stone wall, aqueduct La Malga
Fig. 2: slightly layered rubble stone wall, aqueduct La Malga

Fig. 3: roman inventory, mortar of opus caementitium wall structures
Fig. 4: roman inventory, arch stone and horizonal layer

Fig. 5: roman inventory, specus
Fig. 6: roman inventory, specus mortar and specus sinter crust

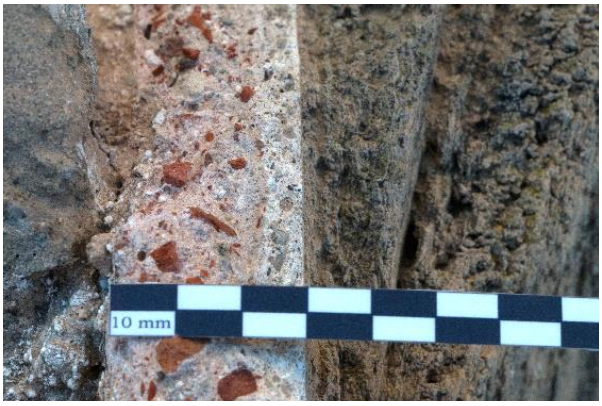

Fig. 7: roman inventory, specus mortar wall
Fig. 8: “mortar with ceramic fragments”

Fig. 9: re-use inventory, wall plaster on top of roman rubble stone wall
Fig. 10: restoration / reconstruction phase, horizontal concrete surface

Fig. 11: restoration / reconstruction phase, reconstruction of vaults and spandrel walls north side
Fig. 12: restoration / reconstruction phase, detail masonry stones and joints

Fig. 13: restoration / reconstruction phase, reconstruction of the vaults south side
Fig. 14: restoration / reconstruction phase, reconstruction underside vault

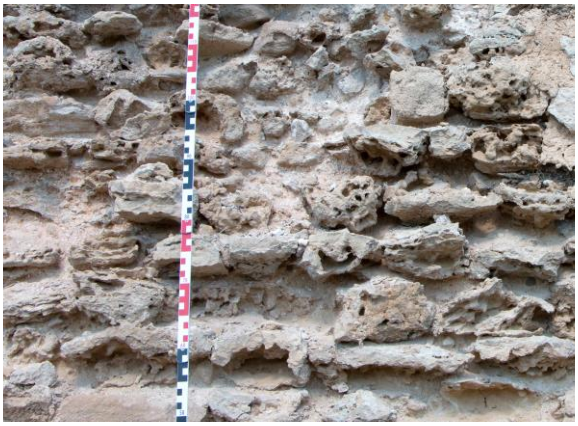

Fig. 15: restoration / reconstruction phase, restoration type II
Fig. 16: damages roman masonry

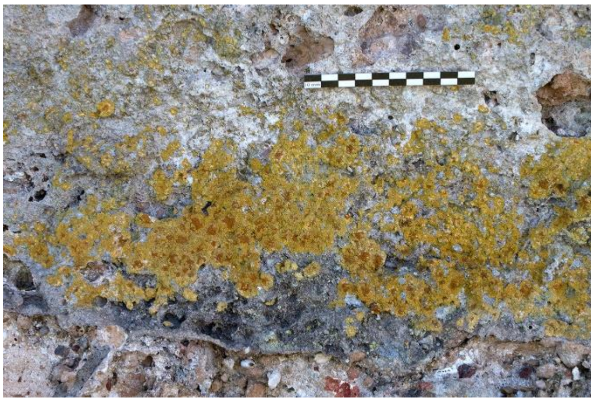

Fig. 16a: damages roman masonry, detail alveolisation masonry stone
Fig. 17: lichens


Fig. 18: plants
Fig. 19: salt efflorescence and damaged mortar


Fig. 20: black deposit / crust underside vault
Fig. 21: delamination of sand-limestone


Fig. 22: vertical crack north side
Fig. 23: collapsed arch, aqueduct

Fig. 24: vault masonry, cisterns
Fig. 25: vault mortar, cisterns

Fig. 26: arch stones, cisterns
Fig. 27: shield and spandrel walls, cisterns

Fig. 28: mortar shield wall, cisterns
Fig. 29: residues of facade structures, cisterns

Fig. 30: plaster exterior drain channel, cisterns
Fig. 31: plaster interior, cisterns

Fig. 32: restoration/reconstruction exterior, cisterns
Fig. 33: restoration/reconstruction interior, cisterns

Fig. 34: sanding and alveolization masonry stone arch, cisterns
Fig. 35: black crusts, vault interior, cisterns

Fig. 36: biological colonization interior vault, cisterns
Fig. 37: plants exterior drain channel, cisterns

Fig. 38: plaster in the sondages interior with scratchings, cisterns

Appendix

SALTTESTS LA MALGA MARCH 2022

TESTNUMBER	LOCATION/ COMMENT	RESULTS		
		Chloride mg/l Cl^-	Nitrate mg/l NO_3-	Sulphate mg/l SO_4^{2-}
1	AQU_MAL, vault F 26-27, east	<u>0</u>-500	25	>1600
2	AQU_MAL, vault F 26-27, east	0-500	100-250	<200
3	AQU_MAL, vault F 26-27, west	0-500	500	<200
4	CIS_MAL, Comp. 12, inside, shield wall, plaster	0-500	500	<200
5	CIS_MAL, Comp. 12, inside, tunnel wall, east, plaster	0-<u>500</u>	500	<200
6	CIS_MAL, Comp. 12, inside, tunnel wall, west	<u>0</u>-500	25	>1600
7	CIS_MAL, Comp. 12, inside, tunnel wall, black crust	0-<u>500</u>	25	>1600
8	CIS_MAL, Comp. 12, outside, south side, vaulting structure	500	500	<200
9	CIS_MAL, Comp. 12, outside, south side, shield wall	500	500	<200
10	Water used for testing	<u>0</u>-500	10	<200

Rapport de mission

Une mission dans l'Institut Archéologique de Vienne a eu lieu du 15 au 30 juin 2022 dans le cadre du projet d'étude sur le complexe hydraulique romain Zaghouan-Carthage.

L'objectif de cette mission était de définir et d'entamer les études résultant des recherches accomplis par l'équipe tuniso-autrichienne durant les différentes missions de terrain.

Durant cette mission, des discussions avec tous les membres ont permis de définir le plan du rapport final et les différents auteurs des contributions.

Certaines thématiques comme les études pétrographiques des pierres utilisées dans la construction de l'aqueduc ont été aussi fixées et un appel à contribution a été adressée à une spécialiste tunisienne.

Lors de cette mission, j'ai pu aussi profiter de la richesse des bibliothèques de l'Institut archéologique de Vienne pour combler les lacunes en matière de bibliographie et pour faire avancer la rédaction du rapport.

Des visites de certains musées de la ville de Vienne nous m'ont permis aussi d'avoir une idée sur la richesse patrimoniale et culturelle et sur les expériences autrichiennes en matière de muséographie et de scénographie.

Ce séjour à l'Institut archéologique autrichien de Vienne constitue donc une excellente expérience dans mon parcours professionnel.

Hamden Ben Romdhane

Chargé de recherches à l'INP

Translation

Mission report

A mission to the Archaeological Institute of Vienna took place from June 15 to 30, 2022 as part of the project to study the Zaghouan-Carthage Roman hydraulic complex.

The aim of this mission was to define and initiate the studies resulting from the research carried out by the Tunisian-Austrian team during the various field missions. During the mission, discussions with all team members led to the definition of the final report plan and the various authors of the contributions.

Certain themes, such as petrographic studies of the stones used in the construction of the aqueduct, were also defined, and a call for contributions was addressed to a Tunisian specialist.

During this mission, I was also able to take advantage of the wealth of libraries at the Vienna Archaeological Institute to fill gaps in the bibliography and advance the drafting of the report.

Visits to some of Vienna's museums also gave me an insight into the city's rich heritage and cultural heritage, as well as Austrian experience in museography and scenography.

My stay at the Austrian Archaeological Institute in Vienna was therefore an excellent experience in my professional career.

Hamden Ben Romdhane

Research associate at INP

KOEF 02/2020

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

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

Report on the stay in Zaghouan / Tunisia from October 17-24, 2021

Dipl.-Ing. Dr.techn. Gudrun Styhler-Aydın

(Project coordinator)

Introduction

The project focused on the building survey and the conservation-scientific inventory and condition survey of selected sections of the Roman hydraulic complex between Zaghouan and Carthage as a basis for the development of future conservation strategies for this extraordinary ancient water supply system. After an online kick-off workshop on September 1st, 2021, which served to introduce all project participants and coordinate preparatory work steps (literature and archive research, obtaining necessary permits, organizing specific time schedules, etc.), the on-site analyses began in October 2021 in a first project phase. The project coordinator's task was to determine the structural sections of the ancient spring sanctuary in Zaghouan and the aqueduct in the Miliane Valley to be examined on site in coordination with the L'Institut National du Patrimoine (INP), and to coordinate the work.

Project participants

- 4 PhD students of the cooperation partner institutions: I. Mayer (ÖAW-ÖAI), B. Rankl (ÖAW-ÖAI), K. Mighri (INP), K. Dridi (INP)
- G. Styhler-Aydın (project leader ÖAW-ÖAI), H. Ben Romdhane (project leader INP)
- Y. Khemiri (architect INP)
- 1-2 support staff

Aims

The aim of the project coordinator's stay was to ensure that the existing knowledge of the ancient building structure was extensively expanded through the coordinated combined use of building research and scientific-restorative methods in the investigation of defined sections of the spring sanctuary and the aqueduct.

According to the work plan, the following work package had to be implemented:

WP 1 Documentation and analysis of two selected building structures of the Roman hydraulic complex between Zaghouan and Carthage / Tunisia

- Preparation of the survey and conservation-scientific inventory
- High-tech field survey in cooperation of Austrian and Tunisian team members for documentation and analysis of selected structures by using a 3D terrestrial laser scanner
- On-site conservation-scientific inventory and condition survey of the selected areas as basic components for the development of a preservation concept in cooperation of Austrian and Tunisian team members: focus on assessment and recording, non-destructive investigations
- Postprocessing of the recorded data, analysis of the material, preparations of plans and mappings

Tasks

- Determination of the sections of the building structure to be documented and analysed on site
- Fine-tuning the methodology to be used for the building survey and analysis as well as the conservation-scientific inventory and condition survey
- Organisation of work man for necessary cleaning of areas and general support of work at the structure
- Coordination of tasks for all project participants and introduction on site
- Coordination of off-site work: postprocessing of the recorded data, analysis of the material, preparations of plans and mappings
- Organization of a digital data management system for the results of the building survey and analyses
- conduction of regular team meetings on work progress and results
- Organization and implementation of the final presentation of the 3-week field research and discussion of preliminary results

Results

A section with 11 vaulted bays of the aqueduct in the Miliane Valley south of Tunis (Fig. 1) dating to the 2nd century and the temple cella as a spatial unit of the spring sanctuary at the foot of Djebel Zaghouan (Fig. 3) were selected for the current investigations. In both sections, a high-tech building survey was carried out using the terrestrial 3D laser scanner Faro Focus 3D 120S (see report I. Mayer 2021). This geometric recording of the preserved building fabric subsequently forms the basis for the preparation of as-built plans as well as the mappings of construction phases, building material and damages. In addition to the building survey, the masonry techniques and structural materials were described. At the same time, the conservation-scientific inventory and condition survey were carried out. (Fig. 2, 4) In addition to the historical construction and repair phases, special attention was also paid to the restoration and consolidation work of the 20th century, including the modern materials used. Only non-destructive documentation and analysis methods were used. Tests and detailed observation were used, for example, to classify the mineral building materials used in general and to investigate the presence of harmful salts, microorganisms and deposits (see B. Rankl 2021 report).

Following the on-site analyses, all findings were compiled, elaborated and graphically presented in close cooperation between the project staff of ÖAI and INP (see reports by K. Dridi and K. Mighri).

Fig. 1: Building survey using 3D laser scanning at the aqueduct in the Miliane Valley (I. Mayer, ÖAW-ÖAI 2021)

Fig. 2: Non-destructive material analyses on the aqueduct as part of the conservation-scientific inventory and condition survey (I. Mayer, ÖAW-ÖAI 2021)

Fig. 3, 4: Architectural history and conservation-scientific analyses in the cella of the spring sanctuary in Zaghouan (G. Styhler-Aydın, ÖAW-ÖAI 2021)

KOEF 02/2020

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

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

Report on the stay in Maalga, Carthage / Tunisia from March 6-13, 2022

Dipl.-Ing. Dr.techn. Gudrun Styhler-Aydın

(Project coordinator)

Introduction

In addition to the field research already carried out in 2021 at the spring sanctuary in Zaghouan and on selected aqueduct sections in the Miliane Valley, a further research visit took place in Carthage in March 2022. The work was dedicated to the aqueduct section in Maalga/Carthage and the cistern there. The so-called Hafside Aqueduct in Bardo/Tunis (a later addition to the Roman aqueduct route) was visited for comparative studies. The cooperation partner Dr. H. Ben Romdhane from L'Institut National du Patrimoine (INP) made his office in the National Museum of Carthage available to the doctoral students in the project for post-processing and digital preparation of the building documentation. (Fig. 3) The project coordinator's task was to determine the structural sections of the ancient aqueduct and cistern in Maalga to be examined on site in coordination with the Tunisian cooperation partner, and to coordinate the work.

Project participants

- 4 PhD students of the cooperation partner institutions: I. Mayer (ÖAW-ÖAI), B. Rankl (ÖAW-ÖAI), K. Mighri (INP), K. Dridi (INP)
- G. Styhler-Aydın (project leader ÖAW-ÖAI), online: H. Ben Romdhane (project leader INP)
- 1-2 support staff

Aims

The aim of the project coordinator's stay was to ensure that the methods and interdisciplinary workflow successful applied during the field campaign in October 2021 will be continued in the investigation of defined sections of the cistern and the aqueduct in Maalga.
According to the work plan, the following work package had to be implemented:

WP 2 Documentation and analysis of the aqueduct and cisterns of Maalga in selected sections

- Preparation of the survey and conservation-scientific inventory (planning of selected areas for documentation and analysis, discussions on working steps via online meetings between INP and ÖAW-ÖAI, obtaining permission, preparation of survey equipment)
- High-tech field survey in cooperation of Austrian and Tunisian team members for documentation and analysis of selected structures using the 3D terrestrial laser scanner
- On site conservation-scientific inventory and condition survey of the selected areas as basic components for the development of a preservation concept in cooperation of Austrian and Tunisian team members: focus on mapping
- Postprocessing of the recorded data, analysis of the material, preparations of plans and mappings
- Knowledge exchange and discussion via online meetings between Austrian and Tunisian team members

Tasks

- Determination of the sections of the building structure to be documented and analysed on site
- Organisation of work man for necessary cleaning of areas
- Coordination of work packages for all project participants and introduction on site
- Coordination of off-site work: postprocessing of the recorded data, analysis of the material, preparations of plans and mappings, archive research
- conduction of regular team meetings on work progress and results
- Organization and implementation of the final presentation of the 3-week field research and discussion of preliminary results

Results

The successful implemented interdisciplinary workflow from October 2021 was applied again. In selected areas of the cistern complex and aqueduct route in Maalga, a building survey was carried out using 3D laser scanning (see report I. Mayer 2022), including a detailed analysis of masonry and vaults as well as investigations from a conservation-scientific point of view with condition survey and sampling (see report B. Rankl 2022). (Fig. 1, 2)

In contrast to the investigated sections of the aqueduct in the Miliane valley, the structures in Maalga were initially built independently of each other. Although they were connected to each other in a later phase, they probably did not interact functionally. In the 2nd century, the route of the aqueduct was initially laid south of the existing extensive cistern system with 15 vaulted tanks. Only secondarily was the narrow "corridor" between the aqueduct and the south-eastern façade of the cistern vaulted in. In this context, other pipe routes are noticeable, one of which crosses the aqueduct at a different height. Parallel to the route of the aqueduct, there are also further pillars of a water pipe, which were most likely built from reclaimed building material from the aqueduct and indicate an adapted further use of the water supply.
Three areas were selected from this complex sequence of historical construction phases to shed light on key aspects of the structural development. These are the standard design of a tank of the cistern, the close and later built-over distance of cistern and aqueduct as well as the mentioned crossing of two pipelines. Extensive building documentation was compiled for the selected areas and the conservation-scientific inventory was also carried out here.

In addition to the on-site analyses, the team visited the medieval aqueduct section on the Bardo in Tunis (so-called Hafside aqueduct) for comparative studies and successfully conducted research on historical records, plans and photos in the archives of the INP in Tunis (see reports by K. Dridi and K. Mighri).

Fig. 1: Cistern of Maalga/Carthage, conservation-scientific inventory (I. Mayer, ÖAW-ÖAI 2022)

Fig. 2: Building survey of the aqueduct section in Maalga/Carthage (G. Styhler-Aydın, ÖAW-ÖAI 2022)

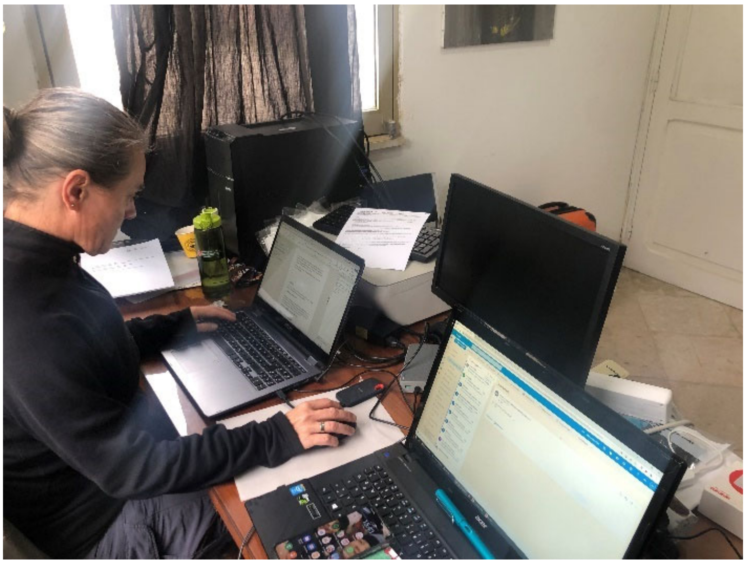

Fig. 3: In the Carthage Museum. Elaboration of the building survey data (B. Rankl, ÖAW-ÖAI 2022)