2025 IMEKO TC26 International Conference on
Metrology for Archaeology and Cultural Heritage
Bergamo, Italy, October 15-17, 2025

Multidisciplinary approach of conservation of the *fistulae aquariae* from the archaeological site of Baiae

P. Fenelli[1], A. De Rosa[1], P. Cennamo[1], G, Trojsi[1], M. Rippa[2], E. Gallocchio[3]

[1] *Department of Humanities, University of Studies Suor Orsola Benincasa, Naples, Italy, alessandro.derosa@studenti.unisob.na.it*
[2] *Institute of Applied Sciences and Intelligent Systems "E. Caianiello" of CNR, Pozzuoli (Na), Italy*
[3] *Ministry of Cultural Heritage and Activities (MIC), Archaeological Park of Campi Flegrei, Italy*

Abstract

This study focuses on the diagnostic investigation and conservation of four *fistulae aquariae* from the submerged archaeological site of Baiae. A multi-analytical approach was adopted to guide restoration strategies. Digital microscopy, FTIR spectroscopy, and XRF analysis provided insights into material composition, protective coatings, and corrosion processes. IRT imaging identified structural anomalies, while DNA metabarcoding revealed microbial colonization by bacteria (e.g., *Micrococcus*, *Citricoccus*) and fungi (*Aspergillus*, *Penicillium*). Based on these findings, a tailored conservation protocol was applied. Cleaning avoided the use of EDTA to prevent lead damage, employing instead ammonium carbonate poultices and cationic resin baths. Mechanical removal of encrustations was conducted where necessary. Aged Paraloid B72 coatings were removed from one artefact and reapplied uniformly across all using a 3% acetone solution. The approach emphasized stabilization over aesthetic restoration, preserving original surfaces and inscriptions. This case highlights the value of integrated diagnostics for informed, non-invasive conservation of marine archaeological metals.

I. INTRODUCTION

The Archaeological Site of Baiae, located in the modern city of Baia, represents an exceptional case within both the Italian and European archaeological landscapes. Distinguished by its extraordinary state of preservation and unique geological and environmental context, the site extends over approximately four hectares and contains significant architectural remains from the Roman era, particularly bath complexes and residential structures of late imperial period.

The historical and environmental development of the site is closely tied to the geodynamics of the Campi Flegrei supervolcano, whose activity has profoundly shaped the region through two major eruptions (approximately 39,000 and 15,000 years ago) and ongoing bradyseismic movements. This latter phenomenon—characterized by alternating phases of ground uplift and subsidence—has been documented since at least the 2nd century BCE. On one hand, it facilitated the underwater preservation of submerged structures; on the other, it required continuous anthropogenic adaptations [1].

The Underwater Park of Baiae stands today as one of the most important sites for underwater archaeology worldwide. The submergence of entire sections of the Roman city has preserved structures and decorative elements in exceptional condition. The first systematic surveys, dating back to the 1960s [2], included seabed mapping and extensive excavations, notably those led by Gianfrotta at Punta Epitaffio. In 1997, an archaeological protection order was established for the marine zone, followed in 2002 by the creation of a protected marine area, officially recognizing the site's environmental and archaeological value.

Within this unique context, the lead water conduits (*fistulae aquariae*) found at Baiae offer a privileged source for studying Roman hydraulic engineering. Produced in various materials—including lead, terracotta, wood, and stone—lead *fistulae* represent the most technically advanced type. Their production involved casting molten lead into stone molds and rolling the sheet around a wooden core, followed by soldering. From the 1st century CE onward, it became common practice to imprint identifying stamps directly into the molds, as described by Frontinus in *De aquaeductu urbis Romae*. These stamps provided information on the manufacturers (*plumbarii*), commissioners, function of the conduit, serviced buildings, and legal status (public or private). The system also incorporated standardized flow regulation mechanisms via the *calix* [3-5].

Fig. 1 Fistulae F1

The *fistulae* from Baiae (Figg. 1 to 4) most likely originated from now-submerged buildings and were recovered during port dredging in the 1920s. However, documentation from the period is fragmentary. Rediscovered in the 1950s by Mario Napoli, 13 *fistulae* bearing inscriptions linked to the Severan dynasty were identified. Among them, specimen F1, attributed to Alexander Severus (222–235 CE), displays distinctive epigraphic features—such as the abbreviation "M" of *Marci* and absence of the *nomen* Aurelius—suggesting centralized production and a terminal role in the water system. A symbol incised on F1 was also found on F3, indicating a potential functional link [6].

Fig. 2 Fistulae F2

F2, which lack inscriptions, present more interpretive challenges, and may have been part of a secondary or urban network, while F3 displays numerical markings of uncertain meaning.

Fig. 3 Fistulae F3

The so-called "fistula of the Pisones" stands out due to an inscription linking it to the villa of the renowned senatorial family, dating to the 1st century CE.

Fig. 4 Fistulae F4

The conservation of the *fistulae* from F1 through F4 (Fig. 1), which constitutes the subject of this work, aimed at stabilizing rather than restoring their appearance.

II. MATERIALS AND METHODS

The protocol used to evaluate and characterize the degradation degree of the *fistulae* comprises an array of notable techniques, which constitute the state of art of diagnostics for cultural heritage.

- Digital microscopy using a Dino-Lite (50x-1000x) portable microscope to observe the global patterns of patinas and formations.
- FTIR (Fourier Transform Infrared) spectroscopy, using a Nicolet iS 10, Having the following
- characteristics: dried and sealed optical bench, spectral resolution: better
- than 0.4 cm-1. Wavelength precision: 0.01 cm-1. Spectral range: 7,800-350 cm-1. semi-quantitative technique used to highlight the presence of both organic and inorganic compounds, in order to identify pigments but also binders and varnishes, thus enabling inferences about previous restoration interventions.[7]
- XRF (X-Ray Fluorescence) analysis, Using a portable SPECTRO xSORT technical data Unit: Value Operating voltage range 9.0 –12.6 V X-ray tube Rh anode, up to 50 kV, up to 125 µA, max.2.5 W Detector SiPIN or SDD Power input during testing 11 W Power input during stand-by 6W Storage conditions -20 – +50 °C; -5 – 120 °F Temperature range during start-up +5 – +40 °C; 41 – 104 °. Used to determine the chemical composition of samples (most notably, the concentration of metals) and characterize the material nature of the artifacts.[8]
- Infrared thermography (IRT) has proven to be a powerful non-contact, non-destructive imaging

technique [9, 11]. Pulsed Thermography (PT), which involves thermally stimulating the sample using a flash or halogen lamp, has been successfully applied in the cultural heritage field for the investigation and analysis of a wide range of artworks and historical artifacts [12-13].

PT analyses were conducted following a consistent protocol for the investigation of the *fistulae plumbea*. A FLIR X6580sc infrared camera (cooled InSb detector, MWIR spectral range: 3.5–5 µm, FPA: 640 × 512 pixels, NETD: 20 mK at 25 °C), equipped with a 50 mm germanium lens (IFOV: 0.3 mrad, spatial resolution ~150 µm), was used to record thermal frames. Camera settings and thermal data acquisition were managed using ResearchIR software (FLIR Systems Inc., Wilsonville, OR, USA). Thermal stimulation was provided by a flash-lamp system (Zoom Action head, Elinchrom, Renens, Switzerland) powered by a Digital 2400 RX generator, delivering a 10 ms, 2400 J pulse from a distance of approximately 50 cm. Thermal image sequences were recorded before, during, and after stimulation at a frame rate of 128 Hz. The mean emissivity of the *fistulae* surface was evaluated using a calibrated blackbody reference disc, yielding values ranging from 0.87–0.93 pre-restoration and 0.81–0.85 post-restoration; these values were considered into the thermal data analysis. All experiments were conducted in a controlled laboratory environment at 24 °C and 55% relative humidity.

- Finally, an integrated biological characterization approach was carried out using classic culturing techniques and the high-throughput Illumina sequencing approach (BMR Genomics, Padova, Italy) to obtain molecular taxonomic annotations. Samples were collected using sterile scalpels and cultured on Petri dishes with LB-Agar for bacterial inference and Malt Extract Agar for fungal inference. After three days of growth, genomic DNA was extracted using a modified C-Tab protocol [14] and subsequently amplified via PCR using specific hypervariable markers: 16S for prokaryotes and 18S for eukaryotes [15-16]. The DNA sequences obtained through the Illumina method were subjected to primer removal, demultiplexing, denoising and general quality check through the Qiime2 environment. The obtained datapool was finally launched against the Silva (16S, bacteria) and PR2 (18S, eukaryotes) databases for taxonomic annotation [17-18].

III. RESULTS

The diagnostic characterization of the four *fistulae* shed a light on the diverse degradation phenomena affecting the artifacts. Each one was covered with compact environmental particulate and variable calcareous crusts. Digital microscopy, as well as the other imaging techniques employed, revealed hidden perforations and a section of bright, uncorroded metal—likely a welding residue—on the F1 sample. F2, being the most visibly deteriorated, featured thick crusts and a more notable presence biological patinas (Fig. 5), possibly marine in origin. F3, though structurally better, still presented a large tear and adherent sulfide crusts.

Fig. 6 Detail of the degradation

By means of FTIR spectroscopy (Fig. 6), it was possible to infer that F4, linked to the Pisones, showed a previously undocumented protective coating—Paraloid B72—which had slowed corrosion but was unevenly applied. This substance is an acrylic resin commonly used for the conservation of metallic surfaces. Over time, the protective film exhibited signs of degradation, compromising its adhesion and reducing its protective efficacy. Differently from F4, F1 and F3 showed no sign of previous intervention.

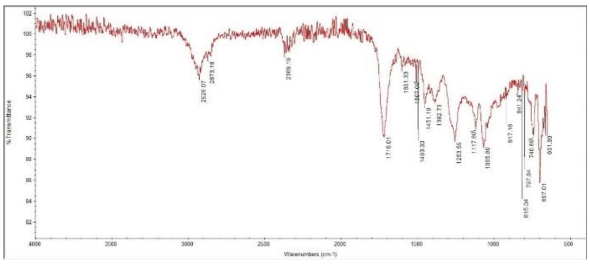

Fig. 5 Results of FTIR

The spectral analysis through XRF, shown in Fig. 7, enabled in-situ elemental analysis of selected points (P1 to P5). The results are summarized as follows:

- **P1 (intact area of the *fistula*):** Predominantly lead, with detectable sulfur likely related to sulfur emissions from the underlying seabed ground. The presence of nearly pure lead indicates a high technological level and considerable economic resources in ancient Baiae.
- **P2 (F3 weld):** A lead-tin alloy was identified, along with traces of iron, sulfur (associated with hard encrustations), and calcium—likely a result of marine calcification (Fig. 3).
- **P3 (F1 inscription):** Lead, iron, and calcium were detected, along with unexpected traces of copper, probably due to contamination from earlier metallurgical processes, rather than being part of the original alloy.

P4 and P5 (F2 crust):

- **P4 (external surface):** A high calcium concentration was detected. The presence of iron is possibly related to the metal supports used during storage.
- **P5 (surface in contact with the metal):** Lead was predominant, confirming the formation of a lead carbonate patina between the metal and the calcareous crust.

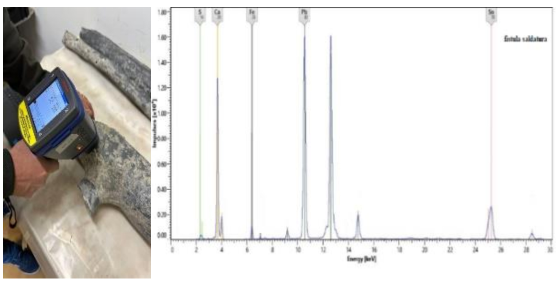

Fig. 7 XRF spectrum obtained from point P2.

PT analysis was conducted on the four fistulae included in the study. For each specimen, Maximum Temperature Gradient (MTG) maps were computed and analyzed based on the PT data. These maps represent the induced thermal variation (ΔT) calculated for each pixel.

A target surface temperature increase (ΔT) of approximately 8 °C was established, which was sufficient to detect material heterogeneities while avoiding any risk of damage to the artifacts. Preliminary calibration tests were performed to ensure that this ΔT value was consistently achieved during all measurements. As an example, Fig. 8 shows the visible images and corresponding MTG maps for the F2 fistula, acquired both before and after restoration. To enhance spatial resolution, the fistula was virtually divided into two overlapping sections, which were analyzed separately, and the resulting MTG maps were subsequently mosaicked.

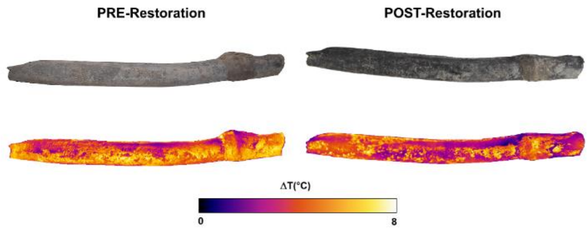

Fig. 8 Pulsed Thermography analysis of the F2 fistula: visible images (first row) and MTG maps derived from the PT analysis.

The MTG maps reveal that, due to the heterogeneous structure of the fistula, comprising lead and adhering soil crusts, thermal responses vary according to local material composition. Areas exhibiting higher ΔT values (yellow regions) correspond to zones more significantly affected by patinas and encrustations, which alter the surface thermal behavior. Conversely, areas with lower ΔT values (violet regions) are less impacted by such deposits, allowing the intrinsic thermal properties of lead, namely, its high thermal conductivity and low specific heat, to dominate the thermal response. By comparing pre- and post-restoration maps, a noticeable increase in regions with low ΔT values is observed after cleaning and descaling interventions. These regions can be attributed to lead surfaces that have been partially or fully cleared of crusts, thereby restoring the material's original thermal behavior. These results highlight the effectiveness of PT in distinguishing surface conditions and assessing the extent of material alteration or restoration. The technique proves to be a valuable diagnostic tool for the non-invasive characterization of artifacts in cultural heritage, offering both spatially resolved and material-sensitive insights.

During the investigation, biological encrustations on the metallic fistulae were examined, and patinas of varying colors—ranging from yellow-green to darker shades—were sampled. Metabarcoding analyses revealed a microbial community dominated by bacteria of the genera *Micrococcus*, *Citricoccus*, and *Kytococcus*, all known for their resilience and prevalence in diverse environments, including marine settings. Specifically, *Micrococcus luteus*, *Citricoccus muralis*, and *Kytococcus sedentarius* were identified as the most abundant taxa. Among eukaryotes, fungi from the genera *Penicillium* and *Aspergillus* were predominant—both widely recognized for their role in biodeterioration due to their ability to degrade both organic and inorganic substrates [19].

The cleaning protocol was developed to avoid the risks of using EDTA on lead [20]. A two-step method was designed: a 15% ammonium carbonate solution was applied in a pulp poultice, followed by a cationic resin in boiling distilled water. Treatments were adjusted by specimen: F1 underwent two cycles with controlled mechanical intervention; F2 required three, including bistoury work; F3 was immersed in cationic solution, though sulfide crusts resisted removal; F4 had its Paraloid removed with acetone before standard treatment.

Fig. 9 Details of F1 before and after restoration

Fig. 10 Details of F1 before and after restoration

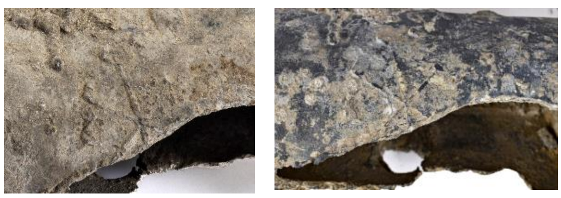

Fig.11 Details of F3 before and after restoration

IV. CONCLUSIONS

In conclusion, the conservation of the *fistulae aquariae* from Baiae was carried out prioritizing structural stabilization over aesthetic restoration (Figg. From 9 to 11). The diagnostic protocol employed in this study combined non-invasive and micro-destructive techniques to achieve a comprehensive understanding of the fistulae's condition. Digital microscopy, FTIR, and XRF analyses revealed the composition, corrosion layers, and past conservation interventions. Pulsed infrared thermography provided high-resolution thermal maps to detect structural anomalies and evaluate cleaning efficacy. Biological diagnostics, including DNA metabarcoding, identified microbial colonizers responsible for biodeterioration. This integrated approach enabled the development of tailored conservation treatments, grounded in scientific evidence, and aligned with principles of minimal intervention and reversibility. Non-harmful encrustations and original deformations were preserved in line with minimal intervention principles. This approach safeguards the archaeological and historical integrity of the artifacts while ensuring long-term stability. F1, in particular, serves as a rare example of a fully identifiable imperial *fistula*. Its features and potential connections to other artifacts support the hypothesis of a centralized workshop for official hydraulic infrastructure. The broader conservation issues, such as dispersion and incomplete cataloging, highlight the need for improved policies on the protection, enhancement, and digitalization of Roman hydraulic heritage. Finally, biological investigations showed how critical and convoluted the preservation of historical artifacts can be, when all iterations of its conservation make them susceptible to potential contamination.

FUNDING

This research was funded by (ITA) Project PE 0000020 CHANGES – CUP B53C22003780006 PNR Mission 4 Component 2 Investment 1.3, Funded by the European Union - NextGenerationEU.

REFERENCES

[1] A. Cova, E. Belvedere, Emergere. “Rivivere la memoria sommersa di Baia, Politecnico”, ARC I - Scuola di Architettura Urbanistica Ingegneria delle Costruzioni, Milano, 2019/2020.

[2] N. Lamboglia, “I diari di scavo di Nino Lamboglia a Baia 1995/1960”, ASD IRECO, Roma, 2002.

[3] Plinio il Vecchio, “Naturalis Historiae”, XXIII.

[4] Vitruvius, "De Architectura", VIII.
[5] Frontino, "De aquaeductu Urbis Romae", CXXII.
[6] Aniello Parma, "Le fistulae aquariae dal ninfeo di età severiana a Baia", API INGEGNOSE - ANNO XIII, No.11, 2023.
[7] I. G. Adrover, Applicazioni della spettrofotometria IR allo studio dei beni culturali, Padova 2001, pp. 9-12.
[8] C. Seccaroni, P. Moioli, Fluorescenza X. Prontuario per l'analisi XRF portatile applicata a superfici policrome, Firenze 2002, p. 23.
[9] V. Vavilov, D. Burleigh, "Infrared Thermography and Thermal Nondestructive Testing", Springer Nature Switzerland, pp.598, Berlin, 2020.
[10] M. Vollmer, K. P. Mollmann, "Infrared Thermal Imaging: Fundamentals", Research and Applications, 2nd Edition, Wiley-VCH, pp.794, Berlin, 2017.
[11] A. Di Meo, B. Balbi, M. Casciello, M. R. Vigorito, P. Mormile, M. Rippa, "Complementary infrared imaging methods for the structural and technical analysis of a panel painting: Adoration of the Magi by Marco Cardisco", Infrared Phys. Technol., vol.145, No.105705, March 2025.
[12] M. Rippa, M. R. Vigorito, M. R. Russo, P. Mormile, G. Trojsi, "Active Thermography for Non-invasive Inspection of Wall Painting: Novel Approach Based on Thermal Recovery Maps", J. Nondestruct. Eval., vol.42, No.63, June 2023.
[13] M. Rippa, V. Pagliarulo, A. Lanzillo, M. Grilli, G. Fatigati, P. Rossi, P. Cennamo, G. Trojsi, P. Ferraro, P. Mormile, "Active Thermography for Non-invasive Inspection of an Artwork on Poplar Panel: Novel Approach Using Principal Component Thermography and Absolute Thermal Contrast", J. Nondestruct. Eval., vol.40, No.21, pp.1-9, February 2021.
[14] J. J. Doyle, J. L. Doyle, "A rapid DNA isolation procedure for small quantities of fresh leaf tissue", Phytochemical bulletin, vol. 19, No.1, pp. 11-15, 1987.
[15] S. Takahashi, J. Tomita, K. Nishioka, T. Hisada, M. Nishijima, "Development of a Prokaryotic Universal Primer for Simultaneous Analysis of Bacteria and Archaea Using Next-Generation Sequencing", Plos One, vol.9, No.8, August 2024.
[16] S. Lambert, M. Tragin, J. Lozano, J. Ghiglione, D. Vaulot, F. Bouget, P. E. Galand, "Rhythmicity of coastal marine picoeukaryotes, bacteria and archaea despite irregular environmental perturbations", The ISME Journal, vol.13, pp. 388-401, September 2018.
[17] C. Quast, E. Pruesse, P. Yilmaz, J. Gerken, T. Schweer, P. Yarza, J. Peplies, F. O. Glöckner, "The SILVA ribosomal RNA gene database project: improved data processing and web-based tools", Nucleic Acids Research, vol.41, No.1, pp.590-596, January 2013.
[18] L. Guillou, D. Bachar, S. Audic, D. Bass, C. Berney, L. Bittner, C. Boutte, G. Burgaud, C. de Vargas, J. Decelle, J. del Campo, J. R. Dolan, M. Dunthorn, B. Edvardsen, M. Holzmann, W. H. C. F. Kooistra, E. Lara, N. Le Bescot, R. Logares, F. Mahé, R. Massana, M. Montresor, R. Morard, F. Not, J. Pawlowski, I. Probert, A. Sauvadet, R. Siano, T. Stoeck, D. Vaulot, P. Zimmermann, R. Christen, "The Protist Ribosomal Reference database (PR^2): a catalog of unicellular eukaryote Small Sub-Unit rRNA sequences with curated taxonomy", Nucleic Acids Research, vol.41, No.1, pp.597-604, January 2013.
[19] B. Gutarowska, "Moulds in biodeterioration of technical materials", Acta Universitatis Lodziensis. Folia Biological et Oecologica, vol.10, pp.27-39, November 2014.
[20] M. De Keersmaecker, M. Dowsett, M. Adriaens, "How to Preserve Lead Artefacts for Future Generations", Leuven, Belgium, 2018.