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Microbiology and Archaeology.

Microbial Impacts at Historical Sites during Excavation and Conservation

1. Introduction[1]

The importance of microbial impacts in the alteration and deterioration of cultural artifacts made of mineral, metallic or organic materials has been widely acknowledged in the course of many recent investigations.[2] While in the past biodeterioration problems on cultural artifacts were often handled without a profound analysis and in consequence were simply controlled by biocidal treatments, a much deeper interdisciplinary understanding of the environmental factors and material properties regulating the biogenic damage factor would allow more specific, practical and adequate action.[3]

2. Fundamentals

2.1. Microrganisms and Materials

The microflora of inorganic and organic materials usually represents a complex ecosystem which develops according to prevailing climatic conditions, the input of inorganic and organic substrates as well as the physico-chemical characteristics of the respective material.[4]

In general, the following groups of microorganisms can be proven in variable quantities and dominance of species:

- Photolithoautotrophic microorganisms such as algae and cyanobacteria, which use sunlight as their energy source for growth and release oxygen during the photosynthetic process. Thus they are able to cover their carbon requirements by the fixation of atmospheric CO_2.
- Lichens form a unified vegetation body in a symbiotic association of a fungus (mycobiont) and an alga or cyanobacterium (phycobiont). The form-giving fungus utilises organic nutrients from the alga originating from photosynthesis; in return, the alga is supplied with minerals deriving from the biocorrosive activity of material-penetrating hyphae of the fungus due to the excretion of lichenic acids. In the complex aggregation the alga is furthermore protected from desiccation and other unfavourable influences.
- Chemolithoautotrophic bacteria, which use inorganic hydrogen-donators (NH_4^+, NO_2^-, H_2S, thiosulphate or elementary sulphur S^0) gaining energy by their subsequent oxidation. This metabolic process leads to the release of nitrous acid (*Nitrosomonas spec.*), nitric acid (*Nitrobacter spec.*) or sulphuric acid (*Thiobacillus spec.*). Autotrophic microorganisms receive their required cell carbon even from CO_2-fixation. Some bacteria from this group can grow mixotrophically, meaning the assimilation of organic nutrients for the anabolic formation of cell substance (chemolithomixotroph).
- Chemoorganotrophic bacteria and fungi, whose energy supply is based on the oxidation of organic substrates. In some cases these microorganisms are even capable of gaining energy through the oxidation of metal cations such as Fe^{2+} or Mn^{2+}. Their cell carbon requirements are met in this case by autotrophic CO_2-fixation.

While the first three groups of microorganisms have frequently been described in the past in connection with the biodeterioration of historical sites, most recent investigations stress the previously underestimated spread and ecophysiological significance of chemoorganotrophic bacteria and fungi, especially coryneform actinomycetes and dermatiaceous fungi, on primary microbial colonisation and the resulting biodeterioration processes.

Due to their flexible nutritional requirements, as well as their capability of forming slimy biofilms which cover the material surfaces, the material-adapted microflora is in the position to successfully counter expositionally determined (i) temperature and humidity fluctuations, (ii) ionic-osmotic stress and (iii) nutrient limitations. The occurrence of phototrophic and chemoorganotrophic microorganisms on natural stone surfaces signifies a preparatory material-conditioning for the subsequent colonisation of chemolithotrophic microorganisms.

The above mentioned groups of microorganisms are specifically interdependent on each other during the colonisation on materials, characterised by the formation of coherent biofilms and the utilisation of the various available nutrients by a cometabolic network. Thus single contaminants referring to one distinct physiological group of microorganisms are found only scarcely on exposed materials. With regard to their different physiological characteristics, the previously described group of microorganisms gives rise to different biogeochemical and biogeophysiological damage processes which will be dealt with in the next section.

2.2. Biodeterioration Mechanisms

Whether as a single or a catalytic enhancing factor, because of their contamination, growth and metabolic activity microorganisms such as algae, cyanobacteria, lichens, bacteria and fungi influence the complex interaction between various types of materials and the surrounding physical as well as chemical damage functions (Fig. 8).[5]

Fig. 1. Lintong, Museum of the Terracotta Army, pit no. 2: Terracotta Warrior with consolidated polychromy (1999).

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[1] The work presented here was partly supported by grants from the German Ministry of Foreign Affairs (BMAA) as well as the German Ministry of Research and Education (BMBF).

[2] May et al., 1993; Warscheid – Braams, 2000.

[3] Warscheid, 1999.

[4] Warscheid – Krumbein, 1996.

[5] Koestler et al., 1992.

Fig. 2. Pommersfelden, Castle Weissenstein, detail: Microbial biofilm penetrating into the pore system of a natural stone (i.e. Burgsandstein) as visualized by red PAS-staining.

In the course of biofouling (e.g. presence of colloidal microbial biofilms on or inside the materials) the microflora leads not only to aesthetically impairing discoloration by biogenic pigments (e.g. green chlorophyll, brownish melanin, red carotinoids) but also to the alteration of physico-chemical characteristics of the materials with regard to their (i) mechanical properties, (ii) surface absorbency/ hydrophobicity, (iii) diffusivity and (iv) thermal-hygric behaviour.[6]

Subsequently, the microbial consortia may cause a biocorrosive attack (e.g. microbial induced or influenced corrosion on materials) leading to the alteration of the structure and stability of materials by (i) phototrophic enrichment of organic biomass, (ii) selective cellular enrichment and redox processes of cations and anions (e.g. iron, manganese), (iii) excretion of immediate corrosive metabolic products (e.g. organic and inorganic acids), and (iv) enzymatic mineralisation of respective organic materials.[7]

Moreover, germs, spores, dead cells and microbial toxins (e.g. endotoxins, mycotoxins) possess an allergenic or pathological capability that affects restorers and conservators as well as visitors and users of cultural artifacts, especially in libraries and archives.[8]

3. Environmental Conditions for Biodeterioration Processes

During the anamnesis of biodeterioration processes on cultural artifacts it is important to document the environmental conditions which are favourable for microbial infection, contamination and the biodeterioration process in particular, in order to consider and establish effective countermeasure strategies already at the beginning.

3.1. Biofilm – a stabilising microniche

It is important to stress the fact that a material specific microflora is preferably embedded in a colloidal slime layer, called biofilm (Fig. 2–3). The biofilm protects the microorganisms by balancing changes in humidity and temperature as well as osmotic- and pH-relevant influences due to the presence of colloidal polymeric substances. Based on its considerable ion-exchange capacity, it even resists the penetration of biocides, detergents or antibiotics impeding the control of the microbial contamination and biodeterioration processes in the long-term.

In addition, the arrangement of microbial consortia in a biofilm matrix leads to the stimulation of their metabolic activity by (i) the extension of the colonisation area, (ii) the deposition and enrichment of nutrients on the adhesive surface, (iii) the promotion of a microbial metabolic network ("cross-feeding") and (iv) the support of the intracellular communication by the exchange of genetic information. Therefore, in contrast to medical microbiology, "pathogenic" impacts of microorganisms on materials refer only rarely to the activity of one species, but are more often caused by complex microbial consortia characterised by a high adaptability and flexibility during the biodeterioration process.[9]

3.2. Exogenic Parameters

The microbial contamination on and in materials is basically determined by the availability of water provided by rainwater, rising dampness and condensational moisture, depending on the sorption isotherms of the respective material. Fungal growth will be enabled within a water activity (e.g. ratio of the vapour pressure of the air in equilibrium with a substance or solution divided by the vapour pressure at the same temperature of pure water) of $a_w > 0.6$ and a time of wetness TOW > 0.5 (e.g. more than 12 h during a day); optimal conditions for their growth will be given within an a_w 0.75.[10] Other microorganisms such as algae or bacteria probably need a higher moisture supply ($a_w > 0.9$), but in the widespread presence of moisture-conserving biofilms these microorganisms may survive in infected materials even under more unfavourable moisture conditions.[11]

In the long-term, the material structure (e.g. surface roughness, absorbency / hydrophobicity, porosity and inner surface) determines the adhesion, colonisation and spreading of the microorganisms on and within the material.[12] Its chemical composition may additionally support the microbial succession by providing internal inorganic and organic nutrients. Further decomposable nutrient sources may be offered by the exposition to light, leading to the enrichment of photosynthetic biomass, as well as the deposition of natural and anthropogenic aerosols.[13] In evaluating the nutritive conditions for a particular microbial consortia, it is important to consider that microorganisms settling on material surfaces are able to survive or even grow under oligotrophic conditions (i.e. low concentrations of nutrients).[14] The contamination process will even be extended

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[6] Warscheid, 1996a.
[7] Warscheid – Krumbein, 1996.
[8] Gallo, 1993; Hödl, 1994a.
[9] Flemming – Schaule, 1994; Warscheid, 1996a.
[10] Adan, 1994.
[11] Flemming – Schaule, 1994.
[12] Warscheid et al., 1993.
[13] e.g. ammonia, nitrate or combustive or biogenic hydrocarbons: Warscheid et al., 1991; Warscheid et al., 1993; Saiz-Jimenez, 1995; Mitchell – Ji-Dong., 1999.
[14] May et al., 1993.
[15] Warscheid – Kuroczkin, 1997.
[16] Warscheid et al., 1988.
[17] Warscheid – Kuroczkin, 1997.
[18] Wendler, 1997.
[19] Koestler, 1999; Tiano et al., 1999.
[20] von Plehwe-Leisen et al. 1996; Warscheid – Kuroczkin, 1997.
[21] Kumar – Kumar, 1999.

when buffering capacities for biogenic metabolic compounds with acidic properties are in the respective material, since the optimum of pH for most of the microorganisms studied on cultural artifacts varies around the neutral point.

The optimal temperature for most of the microorganisms involved in the biodeterioration of cultural artifacts ranges between 16 and 35°C. The oxygen supply will not exclude microbial activity, but will determine the type of the respective metabolic pathways, whether oxidative or fermentative. Finally, the possible ways of contamination (e.g. air-borne, infected materials) have to be analysed and considered as a potential cause of microbial infections and biodeterioration processes on historical objects.

4. Protective Treatments in General

The control of biodeterioration processes on materials will basically be achieved by effective measures to limit and restrict the above-mentioned growth conditions for the respective microflora. Therefore, "good housekeeping" and climate control as well as the selection and application of appropriate, particularly microbial-resistant protectives should preferably be guaranteed before applying ecotoxicologically questionable and unhealthy biocides.[15]

4.1. "Good housekeeping" and Climate Control

The protection of cultural artifacts against biodeterioration will be primarily achieved by the reduction of moisture in and around the endangered object in the course of drying, drainage, ventilation or air-conditioned storage. Due to the moisture-conserving effects of microbial biofilms, already contaminated artifacts will probably be kept more safe at humidity levels less than 55 r.H. %, whereas non-contaminated objects will allow up to 65 r.H. %, depending on the respective type of material and its sorption isotherm.

The growth-controlling effect of desiccation will be intensified by a subsequent soft cleaning (e.g. vacuum cleaner, brushes) and, if necessary, careful disinfection (e.g. medical alcohol, possibly combined with conserving agents) of the material surface to remove moisture-absorbing dust, attached particles, crusts or biogenic slimes. In this context, it has to be emphasised that during cleaning the input of additional moisture should be limited as much as possible (e.g. by wrung-out cloths, fine-part dry cleaning); otherwise the cleaning effect will remain only temporarily until the remaining microflora has recovered in the moist condition.[16]

The long-term effect of these measures will be extended as long as the further contamination of the respective objects by aerosols, particles and microorganisms can be avoided. This will require the formulation and realisation of technical guidelines for "good housekeeping" (i.e. regular cleaning and repairing, equable heating and ventilation). Modifications in illumination, temperature conditions, pH-range or the redox potential of the affected materials and their environment will have only slight inhibiting effects against the mostly highly adaptable microflora, not to mention the problems involved in their practical realisation.

Nevertheless, this practical action will already provide sufficient relief in most cases of biodeterioration problems on cultural artifacts, even when microbially sensitive materials are present, and the individual steps can be easily integrated into the general conservation work scheme.[17]

Fig. 3. SEM-micrograph of the microbial biofilm showing rod-shaped bacteria embedded in a slimy extracellular matrix, addressed by the PAS-staining in Fig. 2.

4.2. Selection of Protective Agents

The application of protective agents such as coatings, consolidants, water repellents, fillers, fixatives and organic binders should primarily be carried out with respect to the prevailing physico-chemical conditions of the object's material and its damage situation.[18] If microbial contamination and biodeterioration processes are clearly proven, the selection of respective protective agents should consider their microbial resistance in order to avoid the initiation, reoccurrence or even acceleration of microbial impacts on the cultural objects in question.[19]

The microbial resistance of materials should preferably be tested with material-specific microbial consortia under laboratory conditions as well as *in situ* on the cultural object in question.[20]

4.3. Biocidal Treatments

In the more serious cases of biodeterioration, where the possible improvement of given material-specific, expositional and environmental conditions are inevitably limited and can not be changed, further countermeasures will be required. In order to increase the durability of restoration and conservation treatments on cultural artifacts heavily affected by biodeterioration processes, the use of biocides as additives might be unavoidable here.[21]

Antimicrobial active substances can be commonly categorized as alcohols, aldehydes, organic acids, carbonacidesters, phenols and their derivatives, halogenated compounds, metals and metal organic substances, oxidative compounds, enzymes, surface-active compounds and various synthetic organic products.

Commercial biocide products used in classical conservation with rather rapid effects mainly include

1. quaternary ammonia compounds,
2. chlorine or halogenated compounds,
3. metal-organic compounds
4. aromatic compounds (e.g. phenols, formaldehyde, CMK) or
5. isothiazolinone-derivatives.

Alternative active substances, which are more easily handled in conservation practice because of their low toxicity, might include

- metallic salts (e.g. copper, zinc)[22],
- acetic or salicylic acid[23],
- borax ("polybor")[24],
- PHB-esters[25],
- ethereal oils (e.g. thyme-oil, rose-oil, neem-oil), or
- pyrethrum.

The application of these alternatives naturally requires more patience concerning the overall killing effect. Moreover, it takes for granted that the microbial infection on the treated object will be monitored and sufficient subsequent care will be exercised; in fact this ideally should be the case for every cultural artifact after restoration and conservation!

The formulation of synergistic working biocidal agents could probably result in an increase of their effectiveness whilst reducing the chemical load on the contaminated material as well as the toxicological risk for the restorers and conservators making the application. A major gap in our knowledge is obvious here and needs to be filled by further leading ecotoxicological research.

Since the impact of ionizing radiation or UV-irradiation will probably be limited to an antiseptic treatment of material surfaces, a complete sterilisation of highly infected cultural artifacts will be obtained by the application of ethylenoxide in computer controlled chambers.

It has to be emphasized that the theoretical effectiveness of antimicrobial substances might be strongly reduced in practice due to the physiological and ecological flexibility of the microbial consortia embedded in the colloidal biofilm on the respective materials in situ as mentioned above.[26] Especially the cometabolic organisation of the respective microflora makes organic synthetic structured biocides in the long-term highly susceptible as nutritive substrate, thus reestablishing the preceding biodeterioration processes. In consequence and with regard to the design and use of microbiocides, proof of their effectiveness against a broad spectrum of material-specific microorganisms has to be given in order to avoid later selectivity, adaptation and resistance by the prevailing microorganisms. Over and above that any possible detrimental side-effects for the treated material in terms of colour changes, corrosion or internal crystallisation has to be avoided and tested preliminarily in laboratory studies.[27] Finally, ecotoxicological considerations demand careful use of biocidal additives in order to limit a possible health risk for the conservator doing the application as well as later visitors to the cultural artifacts.[28]

Fig. 4. Lintong, Museum of the Terracotta Army, pit no. 2, detail: Whitish fungal contamination on terracotta fragments in an excavation area (June 1998).

5. Microbiological Material Analysis

Attention to biodeterioration problems by people in charge of the restoration and conservation of the cultural heritage has revealed a growing demand for an entire evaluation of the importance of microbial impacts interacting with material-immanent properties as well as natural and anthropogenic influences during the deterioration process.[29] According to the proposed analytical strategies of May and Lewis (1988) as well as Becker et al. (1994), a consistent analytical approach comprises, in the following order

- object anamnesis (e.g. damage description, object history, climatic/environmental conditions, material properties, former protective treatments),
- non-destructive observations (e.g. videomicroscopy, remission spectroscopy, respiration/photosynthesis measurement, assessment of ATP-content),
- microscopical studies (e.g. biofilm staining procedures (PAS/FDA), light and fluorescence microscopy, SEM, CLSM),
- biochemical measurements (e.g. quantification of proteins / phospholipids as biomass, analysis of pigments), and finally
- microbiological investigations (e.g. enumeration of airborne and material-immanent microorganisms, characterisation and taxonomical classification of the microflora, simulations studies, toxicological studies).

In addition, the biodeteriorating effects need to be proven by a quantification of complementary changes in the material properties (e.g. discoloration, loss of weight, weakened stability, increased roughness, altered structure/porosity, increased absorbency/hydrophobicity). In the course of this work, changes in the physico-chemical behaviour of the material in the environment should be addressed, such as thermal-hygric stresses due to the darkening of the material surface by biogenic

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[22] Richardson, 1988.

[23] Kumar – Kumar, 1999.

[24] Richardson, 1988.

[25] Lesznicka, 1992; Hödl, 1994b.

[26] Tiano et al., 1995.

[27] Wakefield – Jones, 1996; Nugari, 1999.

[28] Warscheid – Kurozckin, 1997.

[29] Koestler et al., 1997.

[30] Warscheid et al., 1991; Warscheid, 1996b.

[31] Hödl, 1994a; Averdieck et al., 1997; Flannigan, 1997.

[32] Allsopp – Tubb, 2005.

[33] Warscheid – Rudolph, 2002.

[34] Krumbein et al., 1993.

[35] Padfield, 2002.

[36] Sedlbaur, 2002.

[37] Warscheid, 1999.

pigments, the tendency for increased deposition of pollutants due to the presence of a sticky biofilm and alteration in moisture transport due to the impact of pore-filling biofilms.[30] In specific cases, the potential hazardous impacts of microbial metabolites to human health (e.g. allergenic spores, toxins, pathogenic microorganisms) should be considered, analysed and additionally evaluated.[31]

6. Microbiology and Archaeology – Case Studies

The microbial impacts at archaeological sites include three major phases: (1) initial decay of vulnerable organic materials right after the burial and/or limited maintenance and care of the respective site during initial months and years, (2) transforming biodeterioration processes during the burying and uncontrolled exposure depending on prevailing environmental conditions over centuries and (3) post-excavation biodeterioration within days and months after the uncovering, safeguarding and conservation of historical artifacts.

The preservation of archaeological sites and their historical artifacts is thus basically favoured by low temperatures, natural dry conditions, artificial and natural preservation (i.e. salts) as well as low oxygen contents in the surrounding environment.

During the transformation period natural mechanical transformers (i.e. water flow, wind erosion, frost and silting), chemical transformers (i.e. acids, aerosols) and biological transformers determine the alteration and deterioration progress, whereas cultural transformations (i.e. ploughing, re-use) should also not be underestimated in this regard. After the excavation of archaeological monuments and artifacts microbial damage is stimulated again by considerable changes of the redox conditions through the enhanced access of humidity, oxygen and nutrients which support the contamination, infection and infestation of the archaeological artifacts by air- or waterborne microorganisms.[32]

Organic archaeological artifacts should not be fundamentally declared to be potential nutrient sources, since there might be a good reason why they have survived for centuries.

For instance, microbiological investigations on the famous polychrome coatings on the warriors of the terracotta army in Lintong (China) have shown that the Oriental lacquer layer with its phenolic compounds is hardly attractive to the fungi contaminating all the rest of the excavation (Fig. 1, 4, 5). The microorganisms present here concentrate more and mainly on the mechanical detachment of the surface paint layers rather than on "eating them up".[33]

Mural paintings, whether based on fresco or secco techniques, offer a wide range of organic binders (e.g. casein, lime, oil, egg yolk) and – in the course of restoration treatments – consolidants and fixatives based on polymeric compounds (e.g. celluloseacetate, PVA, PMA). If sufficient water is available, biodeterioration will be expressed here in detrimental discoloration and/or decomposing biocorrosion, unless biocidal effective pigments (e.g. copper-containing malachite) happen to limit or even control the microbial activity considerably. If overall climatic control can be achieved on these objects and their surrounding environments, biodeterioration processes might be limited and controlled with less or even no application of biocidal additives.

The intensity of the microbial attack on historical glass objects and paintings depends mainly on the composition of the silica material. Especially high concentrations of potassium will make the glass increasingly susceptible for microorganisms and their biocorrosive attack; additives of manganese- and iron-containing minerals will also induce microbial oxidation processes. Nevertheless the biodeterioration processes on glass mainly happen as a secondary effect in the course of preliminary corrosion processes caused by atmospheric pollutants, although they can also be initiated and supported by organic oil and wax varnish residues deriving from former historical restoration treatments. Careful cleaning and sufficient ventilation during treatments will help to control the biodeterioration processes here.[34]

In archives, the impact of microorganisms on the deterioration of paper, parchment, leather and textiles seems to be a classical case of biodeterioration on cultural objects of historical value. Nevertheless, it has to be said that, in addition to the nutritive material, considerable amounts of moisture and humidity are needed to keep the biodeterioration going. Convincing definitions of humidity levels which could be regarded as favourable for microbial growth on archive material are missing and difficult to assess, since the climatic properties of the building and building materials (e.g. building physics, absorbency), the maintenance of objects (e.g. cleaning) and types of materials affected differ from case to case and are presently not fully understood.[35] Moreover, our knowledge of the physiological behaviour of respective microorganisms (e.g. sporulation, germination) under these specific expositional conditions is scarce.[36] If we could reach a better understanding of the prevailing growth conditions of microorganisms in archives, it would be much easier to make environmentally friendly assessments and formulate effective countermeasure strategies.

Thus assessment of biodeterioration endangerment of cultural artifacts, whether archived indoors or openly exposed, including clear proof and differential diagnosis of microbial impacts within the actual deterioration process, will necessarily demand the development of integrated concepts with respect to long-term prevention.[37] The benefit of interdisciplinary and complementary cooperation among archaeologists, conservators and microbiologists in the evaluation and handling of biodeterioration impacts on cultural artifacts will be demonstrated exemplarily in the following case studies based on recent research activities by our laboratory within the framework of conservation practice.

Fig. 5. Lintong, Museum of the Terracotta Army, pit no. 2, detail: Microbial biofilm migrating under the polychromic lacquer layer, accelerating the detrimental detachment process.

Fig. 6. Nydam Mose, a ritual location of the vikings in the south of Denmark: Overview on the excavation site.

6.1. Terracotta Army in Xian / China (polychrome coatings)

In order to improve the conservation techniques for the preservation and protection of the "Oriental lacquer" coating on the terracotta warriors in the mausoleum of the first Chinese emperor Qin Shi Huang in Lintong, the mechanisms of the alteration of the polychrome coatings and their consequences for the conservation treatments were analysed under the coordination of the Bavarian State Office for Preservation of Historic Buildings and Monuments in Munich (Germany) and the Museum of Terracotta Warriors and Horses of Qin Shi Huang in Lintong (China) (Fig. 1).

Microbial contamination could be observed on nearly all materials inside the excavation in Lintong (painted layers, terracotta, wood, loam; Fig. 4). The humidity ranged between 60 and 80%, sometimes reaching the dew point at the bottom of the excavation site. Consequently it was necessary to analyse the microbial contamination on the recovered terracotta fragments and at the excavation site and determine its taxonomical composition, distribution and metabolic activity (e.g. impression plates, quantification of air-borne microorganisms, ATP-analysis), to evaluate the supporting growth conditions (e.g. monitoring of climate data) and to develop effective countermeasures via specific climate controls and subsequent biocidal treatments (e.g. arrangement of test fields).

Within the conservation procedure for the polychrome coatings on the terracotta statues the insidious decomposition of the purely organic priming coat plays an important role. The coating is extremely sensitive to changes of its moisture content and shows extreme dry shrinking and deformation, leading to a steady loss of the historic paints. The conservation procedure starts therefore with the reduction of the dry shrinking and the consolidation of the paint layers; during this procedure, the microbial contamination of the fragments has to be controlled simultaneously at the humidity levels (90–95% r.H.) necessary for the preservation of the non-fixed coatings. In this context it was even necessary to test the consequences of the proposed conservation treatments on the microbial contamination in order to minimise the microbial endangerment of the fragments through adequate selection of protective agents.

The results of the microbiological investigations revealed that fungi are the most important contamination on the analysed fragments and at the excavation site itself; especially in the soil samples the presence of actinomycetes could be proven and various cyanobacteria could be isolated from the terracotta *situ*. The isolated microflora show strong biocorrosive activity, including acid production and manganese-oxidation properties. In addition, the microbial contamination was suspected of causing hygienic problems within the excavation fields. While the function of the lacquer layer as a potential nutrient source could not be proven, the underlying microflora tends to infiltrate and detach the paint layer from the fragments (Fig. 5). This hidden contamination represents an important problem, especially for the preservation of the Oriental lacquer layer on the terracotta warriors.

The regular application of organic biocides had to be evaluated critically. The clayish, loamy soil absorbs and neutralises the active substances of the biocides very rapidly in its clay particles, and in the long-term microbial mineralisation it provides an important nutritive source for the reoccurring microflora. In order to control the biodeterioration problems on the terracotta fragments and at the Lintong excavation site, provisional recommendations called for regular climate control and ventilation in the excavation area in consideration of controlled drying of the lacquer layers and for disinfecting and subsequent biocidal treatment of the loamy soil of the bulwark using medical alcohol and an inorganic biocidal solution (e.g. 5–10% borax in tap water).

The cleaning, impregnation and consolidation of the terracotta fragments showed considerable relief from the microbial contamination and biodeterioration processes. Organic biocidal treatments (e.g. 0.5% CMK in iso-propanol) were sometimes advised during consolidation of the sensitive lacquer layers under high humidity conditions, whereas in most cases the application of medical alcohol was quite sufficient in order to control the infecting microflora during the conservation process.

6.2. Nydam Mose / Denmark (metals)

Recovering archaeological objects results in considerable changes in the environmental conditions the materials are exposed to; oxygen seems to be the most important factor here, sometimes starting or even accelerating biodeterioration

Fig. 7. Nydam Mose: Analytical devices with special designed microelectrode devices (i.e. tube in front) to measure the oxygen levels respectively anoxic areas in the sediments of the excavation field.

processes on metals, wood, leather or textiles. On the other hand, if objects remain in their present environment, such as in sediments, soils and closed caverns, biodeterioration could also continue due to the activity of anaerobic microorganisms, such as sulphate-reducing bacteria or fermentative microorganisms.

Within a Danish research project on "in-situ-preservation" the possibility of safeguarding *in situ* cultural artifacts buried at a historical site in order to postpone costly conservation and maintenance until the future was studied and evaluated at various Viking excavation sites in Denmark.[38]

In Nydam Mose, a ritual location of the Vikings in the south of Denmark, precious metal objects are buried in the muddy, waterlogged sediment of a former brackish-water lake containing sulphate and chloride in various concentrations scattered irregularly over the landscape. In addition the impact of nutrient rich waters from the surrounding farmland (i.e. nitrogen, phosphates, organics) led to a further increase of salt concentrations and also to high oxygen consumption in the soil, causing anoxic conditions around the historical site (Fig. 6).

With the help of specially designed microelectrode devices it was possible to measure the oxygen levels or anoxic areas within a large part of the historical site and to do profile-assessments of the redox conditions of the sediment to a depth of nearly 20 cm (Fig. 7). It could be shown that oxygen-depleted areas were not homogeneously distributed over the whole area. Nevertheless, certain anoxic areas correlated with high concentrations of sulphate and here the presence of potential metal-corroding, sulphate-reducing bacteria could be proven.

In this case, the microbiological assessment of bacterial presence and metabolic activity greatly helped the archaeologists to very precisely address the most microbially endangered areas of the historical sites and to focus on places where archaeological excavations are urgently needed in order to prevent loss of precious metal artifacts.

6.3. Temple of Angkor Vat / Cambodia (natural stone)

The Angkor temple complex is located near the town of Seam Reap close to lake "Tonle Sap" in the centre of Cambodia. The region lies in a tropical climate with intensive dry and rainy seasons. The buildings were built in the period between 802 and 1295. The assemblage of temples represents the largest religious monument in the world; more than 100 temples cover an area of 230 square kilometres (Fig. 8).

The studies described here for conservation of "Apsara" reliefs have been carried out since 1997 at "Angkor Vat", the largest temple of the Angkor complex, as part of the German Apsara Conservation Project (GACP) of the restoration and conservation department at the Polytechnic University of Cologne (Germany) under the direction of Prof. Dr. H, Leisen.

Due to widespread corrosion and scaling of the sandstone, the "Apsara" reliefs in question are in danger of irretrievable loss. In order to develop an effective conservation strategy, it was necessary to analyse the causes of the stone deterioration and to evaluate the influence of the microbial impact.

Based on the experiences and results of earlier and recent microbiological studies by French and Japanese scientists[39] the most typical sites for biodeterioration processes at Angkor Vat were selected for detailed and long-term microbiological studies. In addition, microbiological investigations were also performed at Preah Ko, Preah Khan, Bayon and Banteay Srei in order to produce a very comprehensive view of the biodeterioration processes around the Angkor site.

Fig. 8. Angkor Vat, temple: Natural stone affected by biocorrosive and biofouling microorganisms.

The microbiological studies during 1997 and 2004 comprised the assessment of the quantity and quality of microbial infestations by algae, lichens, fungi, bacteria and actinomycetes within the stone profile, the monitoring of microbial metabolic activity over time and climatic conditions, the analysis of the possible impact of microorganisms on the deterioration of stone, and the development and testing of conservation and biocidal treatments in regard to possible strategies for control of biodeterioration processes.[40]

The microbiological studies by GACP at Angkor Vat and surrounding temples at the Angkor site have revealed that the natural microflora on rocks is represented by a complex and stable microbial community of algae, cyanobacteria, fungi, lichens and bacteria (Fig. 12a-b). The microbial biofilms are mainly located in the uppermost layers of rocks, but certain microbes penetrate even deeper into profile of the stone. The metabolic activity of the microflora (i.e. respiration, photosynthesis) is very high, especially during rainy season, and results potentially in biocorrosive and biooxidation activities due to the excretion of organic acids and the oxidation of iron-containing minerals. Nevertheless the biodeterioration activities in mature biofilms (i.e. lichens) reach a natural balanced climax status, which should not be interfered with unless there is a conclusive and substantial conservation concept, all the more so because the natural microbial biofilm regulates the moisture and thermal absorption of the rocks at the Angkor site.

The consequences of uncontrolled removal of the lichen infestations was demonstrated after biocidal cleaning by an Indian conservation project in the early 1990s. The surface biogenic contamination at Angkor Vat was removed with brushes and highly toxic biocides, leading in the following years to an intensive blackening of the treated, naturally grey stone due to the intensive growth of cyanobacteria (Fig. 9). Considering the thermal effect of blackened surfaces especially in tropical climates, which adds hygric stress to the affected clay-containing stone surface, the developing contamination by the blackening microorganism has to be judged up to this point as a major

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[38] SOERENSEN – GREGORY, 1998.

[39] POCHON et al. 1960; HYVERT, 1968; FUSEY, 1991; JSA 1995–2003.

[40] WARSCHEID, 2004.

Fig. 9. Angkor Vat, temple: The removal of the natural biofilm led to the overgrowth of blackening microorganisms with additional thermal-hygric stresses to the sensible claycontaining sandstone resulting in a severe detachment of rock shales from Apsara carvings.

threat for the endangered stone material, provoking the obvious massive formation of rock shales, in comparison to the moisture-balancing protective biopatina of green algae and multi-coloured lichens (Fig. 10).

Under these considerations the mature microbial biofilm infestations at Angkor Vat and surrounding temples at the Angkor site should remain in place until there is a thorough microbiological analysis and interdisciplinary evaluation. Cleaning or biocidal treatments should be applied only if the entire microbial community present at the Angkor Vat is controlled and only in places where it is essential for the support of stone consolidation treatments or to achieve better visibility or legibility of the historic artifacts. Organic biocides or those containing chloride should be avoided because of their toxicity, the lack of long-term efficacy and possible nutritive effects on remaining or reoccurring microflora. Synergistic treatments, combining the oxidative destabilisation of the microbial biofilms by hydrogen peroxide, soft mechanical cleaning of the stone surface and the subsequent application of metallic salts with depot function offered the most positive effects so far (Fig. 11a-b). In addition, the widespread contamination by fungi necessarily requires the application of microbially resistant consolidants in order to extend the durability of the proposed conservation treatment. In this regard the application of microbially resistant stone protective agents has to follow international standardised testing and proper hygiene at the site. The conservation activities need to be supported by constructive water protection and management. The long-term effect of any conservation treatment has to be ensured by ongoing maintenance and care of the monuments and temples at Angkor site.

Future research activities of GACP in regard to microbiological impacts on the rocks of the Angkor temple complex will include further microbiological ecology studies on the stone-colonising microflora, the evaluation of microbial biofilm damage (i.e. dilatation, drilling resistance, hardness), the microbiological testing of stone protective agents, mortars and coatings, the continuation of biocide field test operations (i.e. new applications, monitoring) and the possible application of bioremedial techniques (i.e. biocalcification, biodesalination) in GACP's ongoing conservation work.

6.4. Archaeological Site of Milet / Turkey (waterlogged marble)

Milet was one of the largest and most important towns in Asia Minor in the 7th and 6th centuries B.C., located about 100 km south of Smyrna, or modern Izmir. Because of the silting of the gulf by the Meander River, which carried large amounts of soil from the Anatolian highlands, Milet is now located about 10 km from the sea.

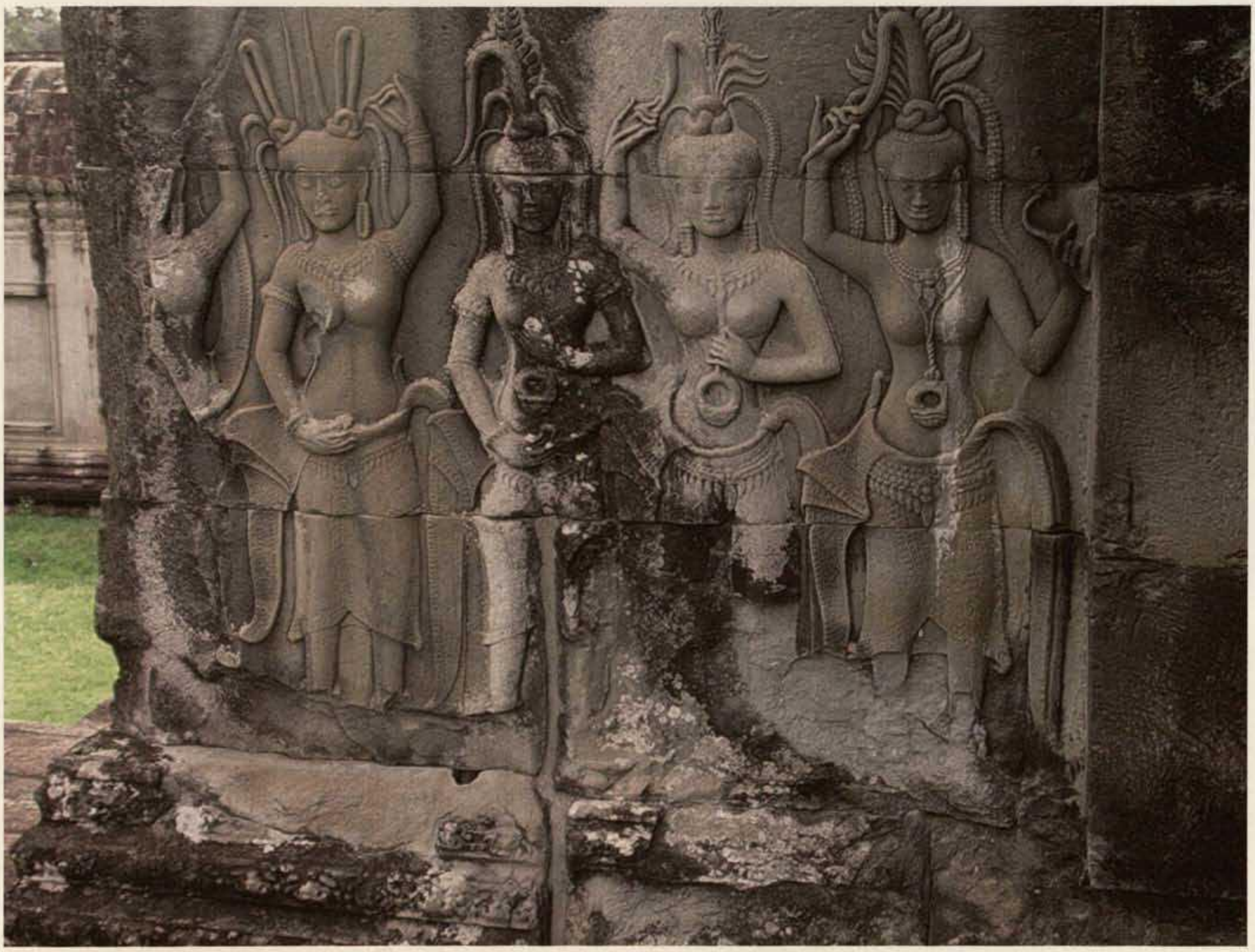

Fig. 10. Angkor Vat, temple, detail: The removal of the natural biofilm led to the overgrowth of blackening microorganisms with additional thermal-hygric stresses to the sensible claycontaining sandstone resulting in a severe detachment of rock shales from Apsara carvings.

During the last century of excavation activities, periodic flooding of the archaeological site of Milet (Turkey) led to a dramatic change in the appearance of waterlogged marble objects through the formation of grey/brownish-to-violet carbonate crusts on excavated marble fragments (Fig. 13).

The rough, porous but compact crusts exhibit a changing thickness from the lower (up to 4 mm) to the upper parts of the artifacts (with no visible crust). Distinct coloured zones can be recognised due to varying water levels: higher parts mainly exhibit a white-grey and lower parts a brownish-black appearance; in the spring, when the water level sinks, the marble fragments are covered with red-to-violet layers, which change to grey again during the dry summer season.

Microscopical, chemical, petrophysical and microbiological analyses have revealed that the surface carbonate precipitation on the marble (Fig. 14a) is mainly caused by the metabolic activity of photosynthetic algae and cyanobacteria within complex microbial mats, typical for the formation of stromatolites in hypersaline marine environments.[41]

The marble fragments covered with those crusts show different forms of damage. On the lower sections larger scales are separating from the marble surface, while the upper sections sometimes show a distinct flaking; the flakes contain marble grains at the back, verifying the damage potential of this crust. Compared to the white marble with well sorted large calcite crystals, the grey sections are characterised by smaller calcite grains which are more poorly sorted. Several layers form crusts like annual rings. Grains of different dimensions and composition are embedded in the crust matrix formed by soil particles, microorganisms and plant residues.

Further biological analysis documented the presence of organotrophic bacteria, fermenting microorganisms, photosynthetic algae and cyanobacteria, anoxygenic sulphur bacteria and sulphate-reducing bacteria, representing a complex microbe system such as can also be observed in stromatolithe formations worldwide.

The presence of the microorganisms and the appearance of the crust layers clearly indicate that crusts are formed by a microbe mat which is activated during the flooding period. In the course of the biogenic formation of fine-grained calcite within this microbial layer (probably using calcium as the ionic part of the water and dissolved carbon dioxide from the air), soil particles and other small compounds of the muddy water may be additionally caught and fixed in the viscous mat. In the summertime when the water level is sinking the biological layers will be dried (mainly in those areas without a sufficient water reservoir from the ground). A hard, grey-to-brown crust is

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[41] BRÜGGERHOFF et al., 1999.

Fig. 11a. Angkor Vat, northern bibliotheca, detail: before the conservation treatment.

formed; representing in type and content the components of the surrounding mud. Microbes partly move back underneath the surface to start growing again when environmental conditions improve during the next flooding cycle. If there is sufficient water available red bacteria types will remain at the surface, sometimes causing an extensive colouring of the objects.

In order to evaluate the possible detrimental or protective functions of those biogenic carbonate crusts and to develop further sustainable conservation strategies, the development of the biogenic precipitations and discolorations was documented and their physico-chemical and microbiological properties were analysed during a seven-year study.

All crust samples at least exhibited similar mineralogical characteristics; differences were only caused by an irregular disruption of the layers (probably caused by dissolution processes) resulting in a very porous and weak structure (i.e. 17 Vol%; median pore diameter: about 5 µm) compared to the porosity of the genuine marble (i.e. 0.3 Vol%; median pore diameter about 0.05 µm). This enormous difference in material structure will cause a difference in thermal expansion behaviour (dark areas at the base of a column were warmed up about 2.5°C more than the higher yellowish white sections), leading to scaling processes in the thick crusts and to slight deterioration of the underlying marble, as shown by ultrasonic measurements. On the other hand hygric measurements revealed that the exterior of the crust forms a water repellent zone at the front, probably due to microbial biofilms, limiting the desiccation of the microbial microenvironment and thus protecting the marble from the penetration of hypersaline salt waters.

Using scientific methods, different cleaning procedures and biocidal treatments (laser, mechanical and chemical procedures) were tested for their efficacy in removal of the aesthetically detrimental crusts and for control of microbial infestations on the marble surfaces at the site, in order to avoid later crust formations (Fig. 14b). In addition, the consequences of those conservation treatments should be subjected to interdisciplinary evaluation with regard to the preservation of historical marble fragments and the sustainability of the interventions.

Mechanical treatment (pneumatic operating chisel, a pneumatic dissecting graver and micro-sandblast equipment) had proven to be a suitable technique in terms of both cleaning results and preservation of the marble surface, but it demands enormous amounts of time.

Future research activities will deal further with the analysis of causes and the dynamics of the biocarbonatisation process due to periodic flooding and will refer recommendations for the conservation of historical artifacts in Milet to other related places of historical importance in the Mediterranean area as much as possible.

7. Future Needs for an Interdisciplinary Approach in Conservation Microbiology

Based on the fundamentals of microbial impact on materials and the case studies presented here any archaeological activities or conservation interventions at historical sites should pay special attention to potential microbial impact on the deterioration of the cultural artifacts or archaeological sites as part of a strong interdisciplinary risk analysis.[42]

Fig. 12a-b. Angkor, temple complex, details: Natural multicoloured biofilms of different photosynthetic microorganisms (i.e. lichens, algae and cyanobacteria), distinctly seperated due to expositional factors and interspecific competition.

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[42] Warscheid, 2003.

In this context, an extensive microbiological analysis within biodeterioration studies of materials in the restoration and conservation of cultural artifacts is mainly dependent on the timely recognition and evaluation of microbially influenced material damages and their hygienic relevance. Relatively non-destructive methods for detection and analysis of biodeterioration processes (i.e. *in situ*-microscopy, remission spectroscopy, contact agar enrichments and molecular biological techniques) are at hand for this.

Basic measures in practice-related conservation of the cultural heritage will start with control of environmental parameters favouring microbial infections and growth. Nevertheless, the preservation of prevailing environmental conditions or their careful alteration towards favourable exposure conditions should always be carefully balanced and analysed for their possible consequences. Moreover, conservation practice is expected to provide a systematic documentation of techniques, materials and treatments in individual cases in order to work out guidelines to enhance or even control biodeterioration processes on cultural artifacts, at the same time minimising the application of microbiocides with respect to ecotoxicological considerations. In addition, biotechnological processes will be developed using biogenic desalination and carbonation capabilities in conservation practice.

Long-term sustainable conservation strategies should therefore be adequately based on physical, chemical and biological interventions respecting the natural balance of the archaeological site in question.

Abstract

In the course of the excavation of archaeological artifacts considerable changes in the prevailing exposure conditions have to be taken into account in regard to the development and application of subsequent conservation treatments. Mostly exposed or buried in moist or/and nutrient rich environments and therefore naturally contaminated by microorganisms, these historical materials are especially endangered by biodeterioration processes due to the excretion of inorganic and organic acids, biooxidation of metals as well as the formation of surface-covering biofilms before and after exposure. The biogenic damage leads to changes of the material properties, enhancement of material disintegration, and consequent loss of original substance and historical information (i.e. polychromic coatings, metal objects, glass paintings, stone carvings, wall paintings and wood). Moreover, health-related impacts of microbial contamination have to be considered in regard to restorers in charge of the conservation of the artifacts. Nevertheless biogenic crusts developed over the long-term might also act as protective barriers and help to preserve archaeological objects from environmental damage. Due to the formation of these mainly surface related biomineralized encrustations it is possible to prove traces of stonemasons' carvings, remains of historical pigments and material modifications even after centuries. With the presentation of different case studies (i.e. China, Denmark, Cambodia and Turkey) the importance of microbial impacts on archaeological artifacts will be evaluated and necessary conservation strategies for improved protection and sustainable conservation treatments of the historical objects in different environments will be discussed.

Fig. 11b. Angkor Vat, northern bibliotheca, detail: Successful application and longterm efficient protection of a specific designed biocidal formulation (four years after treatment).

Zusammenfassung

Mikrobiologie und Archäologie. Mikrobielle Einflüsse bei der Ausgrabung und Konservierung historischer Stätten

Die mikrobielle Einflußnahme an archäologischen Stätten umschreibt im wesentlichen drei verschiedene Phasen: (1) den anfänglichen Verfall empfindlicher organischer Materialien unmittelbar mit Beginn der Erdlagerung bzw. aufgrund mangelhafter Erhaltung und Pflege an den betreffenden Stätten im Laufe der ersten Monate und Jahre, (2) materialverändernde, mikrobiell-induzierte Transformationsprozesse während der Erdlagerung bzw. unkontrollierter atmosphärischer Exposition entsprechend der jeweilig vorherrschenden Umweltbedingungen in den folgenden Jahrhunderten sowie (3) biologische Verwitterung in Folge der Ausgrabung, Sichtung und Konservierung der historischen Artefakte im Rahmen von wenigen Tagen bis Monaten.

Die Erhaltung archäologischer Stätten und der darin befindlichen historischen Objekte wird daher zunächst grundlegend durch niedrige Temperaturen, natürliche Trockenheit, künstliche wie natürliche Konservierung (z.B. Salze) sowie niedrige Sauerstoffgehalt in der umgebenden Umwelt begünstigt. Wäh-

rend der Transformationsphase bestimmen natürliche mechanische Umwandlungsfaktoren (z.B. Wassereintrag, Winderosion, Frost und Schlamm), chemische Einflüsse (z. B. Säuren, Aerosole) sowie auch die vorhandenen biologischen Agenzien (z.B. Mikroorganismen, Pflanzen und Insekten) das Fortschreiten der materialverändernden bzw. -zerstörenden Prozesse, wohingegen auch kulturell-begründete Einflußnahmen (z.B. Plünderungen, Umnutzungen) in diesem Zusammenhang nicht unberücksichtigt bleiben sollten. Mit der Freilegung der archäologischen Stätten und ihrer historischen Funde wird die mikrobielle Einflussnahme erneut stimuliert, insbesondere durch die Veränderungen der Redoxbedingungen im Zuge des verstärkten Zutritts von Feuchtigkeit, Sauerstoff und Nährstoffen, die die Kontamination, die Infektion und den Befall der archäologischen Objekte durch luft- bzw. wassergebundene Mikroorganismen unterstützen.

Im Verlauf archäologischer Ausgrabungen müssen daher die potentiellen Änderungen der jeweiligen Expositionsbedingungen für die betreffenden historischen Objekte in Hinblick auf die Entwicklung und Anwendung nachfolgender Konservierungsbehandlungen angemessen berücksichtigt werden. Überwiegend im feuchten und nährstoffreichen Erdboden eingegraben und von daher bereits natürlich mit Mikroorganismen kontaminiert, sind die betreffenden historischen Objekte verschiedenen Prozessen biologischer Verwitterung, wie der Biokorrosion durch anorganische und organische Säuren, der enzymatischen Biooxidation von Metallen sowie der Anlagerung schleimiger Biofilme im Rahmen des Biofouling ausgesetzt. Die mikrobiellen Schadensprozesse führen zu Veränderungen der Materialeigenschaften, der beschleunigten Materialzersetzung und dem nachhaltigen Verlust an Originalsubstanz und historischer Information (i.e. Farbfassungen, Metallobjekte, Glasmalereien, Gesteinsinschriften, Wandmalereien und Holz). Darüber hinaus müssen auch gesundheitsrelevante Einflüsse des mikrobiellen Befalls in Hinblick auf die Gesundheit der verantwortlichen Restauratoren berücksichtigt werden.

Biologisch-induzierte Krusten können jedoch auch als schützende Beschichtungen für archäologischen Objekte gegenüber schädigenden Umwelteinflüssen dienen. Durch die Bildung derartiger oberflächlich gebundener biomineralisierter Inkrustationen kann es zudem möglich sein, die Spuren ehemaliger Steinmetzarbeiten, den Verbleib historischer Pigmente oder etwaige Materialmodifikationen auch noch nach Jahrhunderten nachzuweisen.

Organisch basierte, archäologische Materialien müssen nicht immer als potentielle Nährstoffquellen und damit mikrobiell gefährdete Objekte bewertet werden, da sicherlich auch gute Gründe dafür bestehen, dass diese Artefakte über Jahrhunderte hinweg haben überdauern können. So haben die mikrobiologischen Untersuchungen an den berühmten polychromen Farbfassungen auf den Figuren der Terrakotta-Armee in Lintong (China) gezeigt, dass die historische Lackschicht mit ihren phenolhaltigen Komponenten keine besondere Attraktivität für den vorherrschenden Pilzbefall in der Ausgrabung darstellte. Die nachweisbaren Mikroorganismen konzentrierten sich vielmehr und hauptsächlich auf die mechanische Ablösung der Farbbeschichtungen als auf deren enzymatische Zersetzung.

Wandmalereien, ob in Fresko- oder Secco-Technik erstellt, bieten zunächst ein breites Spektrum an organischen Bindemitteln (z.B. Kasein, Öle, Eiweiß) sowie – im Zuge nachfolgender Restaurierungen – auch verschiedener polymerer Kleber und Fixative (z.B. Zelluloseacetat, PVA, PMA). Doch nur wenn genügend Feuchtigkeit verfügbar ist, kann sich hier der mikrobielle Befall in einer ästhetisch-beeinträchtigenden Verfärbung bzw. einer zersetzenden Biokorrosion äußern, sofern nicht biozid wirksame Pigmente (z.B. kupferhaltiges Malachit) die mikrobielle Aktivität begrenzt oder sogar nachhaltig behindert. Wenn darüber hinaus eine Einschränkung der Feuchtigkeitsbelastungen durch eine gezielte Klimakontrolle am betreffenden Wandmalereiobjekt beziehungsweise in dessen Umgebung gewährleistet werden kann, können mikrobiell induzierte Schadensprozesse hier auch ohne den weitreichenden Einsatz von keimhemmenden Bioziden eingeschränkt werden.


Fig. 13. Milet, harbour monument: spring flooding within the archaeological site.

Die Intensität von biologischer Verwitterung an historischen Glasobjekten und -malereien wird im wesentlichen durch die Zusammensetzung der silikatischen Werkstoffe bestimmt. Insbesondere hohe Konzentrationen an Kalium können historische Gläser besonders empfindlich für Mikroorganismen und deren biokorrosiven Angriff machen; darüber hinaus fördern mangan- bzw. eisenhaltige Komponenten die mikrobielle Biooxidation. Entsprechende Prozesse an historischen Glasobjekten basieren in der Regel auf einem Sekundäreffekt im Anschluss an vorlaufende Korrosionsvorgänge, die vornehmlich auf atmosphärische Schadstoffe zurückgehen. Dennoch können mikrobiell-induzierte Schadensprozesse an derartigen Objekten auch durch die Zugabe von organischen Ölen, Seifen und Wachsen im Rahmen restauratorischer Behandlungen initiiert und unterstützt werden. Daher ist bei der Wahl der Reinigungs- und Konservierungsmittel im Rahmen der Behandlung von historischen Glasmalereien besondere Vorsicht geboten.

In Bibliotheken und Archiven erscheint der Einfluss von Mikroorganismen auf die Zerstörung von Papier, Pergament, Leder und Textilien als ein klassischer Fall von biologischem Angriff an kulturell wertvollen Artefakten. Allerdings muss auch hier herausgestellt werden, dass neben den nährstoffreichen Materialien auch ausreichende Mengen an Feuchtigkeit notwendig sind, um die mikrobiell-induzierten Schadensprozesse auszulösen. Eine verlässliche Definition der Feuchtegehalte, die für das Wachstum von Mikroorganismen auf Archivmaterialien günstig erscheinen, ist bislang kaum möglich und schwierig zu bestimmen, da hier häufig die klimatischen Eigenschaften der Gebäude und ihrer Baumaterialien (z.B.

Fig. 14a-b. Milet, marble columns: Surficial carbonate precipitation mainly caused by the metabolic activity of photosynthetic algae and cyanobacteria (a) and different cleaning treatments (laser, mechanical and chemical procedures) to remove the aesthetical detrimental crusts (b).

Bauphysik, Feuchtesorption), die Archivpflege (z. B. Reinigung, Staubablagerungen) sowie auch die Art der jeweils betroffenen Archivmaterialien (s.o.) von Fall zu Fall höchst unterschiedlich sind und daher individuell betrachtet werden müssen. Darüber hinaus ist unser Wissen über das physiologische Verhalten der jeweiligen Mikroorganismen (z. B. Sporenbildung, Sporenkeimung) unter den oben genannten, spezifischen Expositionsbedingungen sehr begrenzt und macht insbesondere hier weitere Forschungsanstrengungen notwendig. Ein besseres Verständnis für die jeweiligen Wachstumsbedingungen von Mikroorganismen in Archiven, Museen und anderen historisch geprägten Innenräumen (z.B. Kirchen), würde die Entwicklung und Anwendung umweltfreundlicher und effektiver Behandlungsstrategien gegen mikrobielle Schadenseinflüsse sehr erleichtern und deren Nachhaltigkeit verbessern.

Die mikrobiologische Analyse von biologischer Verwitterung an archäologischen Objekten, ob in Innenräumen oder im Außenbereich, sowie der eindeutige Nachweis und die Bewertung des mikrobiellen Einflusses im Rahmen des vorliegenden Schadensprozesses verlangt nach integrierenden Konzepten, um einen nachhaltigen Erfolg der anstehenden Konservierungsarbeiten zu gewährleisten. Der unmittelbare Nutzen einer fachübergreifenden Zusammenarbeit zwischen Archäologen, Restauratoren und Mikrobiologen in der Einschätzung und Behandlung von mikrobiell-induzierten Schadensprozessen im Rahmen der Ausgrabungen wie bei der Behandlung des Fundmaterials wird in dem hier vorliegenden Beitrag anhand verschiedener archäologischer Fallstudien aus China, Dänemark, Kambodscha und der Türkei erläutert, bewertet und hinsichtlich möglicher Strategien für einen verbesserten Schutz und nachhaltige Konservierungsbehandlungen der betreffenden Objekte unter verschiedenen Umfeldbedingungen diskutiert.

Photo credits

Fig. 1: Bayerisches Landesamt für Denkmalpflege, München (Foto: Archive of the Museum of the Terracotta Warriors and Horses, Lintong); Fig. 2–14: Dr. Thomas Warscheid, Wiefelstede.

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